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LABYRINTH SEAL ANALYSIS

Volume III - Analytical and Experimental Development
of a Design Model for Labyrinth Seals

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A thorough review of the literature concerning labyrinth seals was conducted and the significant geometric and aerodynamic parameters influencing leakage were identified. An extensive data base was accumulated from published and in-house experimental results as the foundation for the development of a Design Model for labyrinth seals. Full-size two-dimensional seal geometries were tested to extend the data range in key areas. The empirically based model was developed using statistical methods to define correlating equations based on the seal parameters. Comparison of the resulting model to experimental data revealed an accuracy of ±5%. Flow visualization studies yielded qualitative descriptions of the internal flow fields and loss mechanisms at work in both straight and stepped labyrinth seals. Measurement of pressures and temperatures in the seal cavities provided data for comparison with theoretical predictions. Hot-wire anemometer data for internal velocity profiles were in qualitative agreement with the Navier-Stokes analyses.

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FOREWORD

This final report describes technical work accomplished during the Labyrinth Seal Analysis program conducted under Contract AF33615-80-C-2014. The work described was performed during the period 15 June 1980 to 30 April 1985. This contract with Allison Gas Turbine Division of General Motors Corporation was sponsored by the Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory, United States Air Force, Wright Patterson AFB, Ohio, with Mr. Charles W. Elrod (AFWAL/POTX) as Project Engineer. Technical coordination was provided by 1st Lt. Keith C. Topham.

The technical effort reported in this volume was performed by Dr. Raymond E. Chupp, Mr. Glenn F. Holle, Mr. Raymond L. Owen, Mr. Thomas E. Scott, and Mr. Donald Tipton. The experimental efforts reported in this volume were performed by Mr. Glenn F. Holle, Mr. John W. Rothrock, Jr., Mr. Steven G. Gegg, Mr. Steven J. Hilpisch, and Mr. Warren S. Sherman. Managerial direction was provided by Mr. Howard G. Lueders and Mr. Peter C. Tramm.

This report was submitted in four volumes in May 1985. Volume I summarizes the Labyrinth Seal Analysis Model. Volume II presents the user's manual for the Analysis Model computer code. Volume III contains the experimental results and summarizes the Design Model based on these empirical data. Volume IV presents the user's manual for the Design Model computer code.

Publication of this report does not constitute Air Force approval of the findings or conclusions presented. It is published only for the exchange and stimulation of ideas.

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1.0 INTRODUCTION

The present trend of gas turbine design has been characterized by significant increases in cycle pressure ratio and turbine inlet temperatures to provide higher thermal and propulsive efficiencies. These trends accentuate the need for improvements in sealing technology and the development of advanced design and analysis capabilities to reduce gas path seal leakage, minimize vent leakage, provide better control over sophisticated cooling circuits, and prevent high levels of seal leakage into critical aerodynamic locations in the turbine gas path.

Labyrinth seal design and analysis methods available today rely heavily on empirical relationships which severely limit the application range. Available analytical formulations which originated many years ago do not take advantage of modern flowfield calculation techniques such as offered by solution algorithms for the Navier-Stokes equations. In addition, empirically derived models do not provide the design engineer with guidance on how to improve the seal efficiency beyond the information that has been determined experimentally.

The Labyrinth Seal Analysis program was, therefore, directed to the development of an advanced labyrinth seal analysis computer code to provide the seal specialist with a tool to calculate and evaluate the details of the seal internal flow field and to assess the effects of subtle geometric changes relative to improving seal efficiency.

To further enhance the predictive accuracy of labyrinth seal performance, the program included the development of an improved empirical design model to provide the calculation of the flow parameter characteristic based on salient geometric and aerodynamic parameters.

The Labyrinth Seal Analysis effort was structured as a three-phase program. Phase I was directed to the analytical development of both an "analysis" model and an improved empirical "design" model. Supporting rig tests, including flow visualization, passage velocity surveys and performance data, were conducted under Phase II. The Phase III effort was devoted to improving the "analysis" program usability.

The "analysis" model, presented in Volume I of this report (66)*, uses numerical solutions of the time dependent, compressible Navier-Stokes equations to provide the aerodynamic details of the seal interior flowfield. Using existing Navier-Stokes computer codes which incorporate a consistently split, linearized block, implicit algorithm, suitable coordinate systems have been constructed to analyze single-knife and multiple-knife straight and stepped labyrinth seals. The continuity, momenta, and energy equations are solved with a mixing length turbulence model or with a two-equation turbulence model based on turbulence kinetic energy and dissipation rate. Typical "analysis" model geometric capabilities permit variations in clearance, knife height, knife thickness, knife sharpness, and, where appropriate, knife pitch, number of knives, and knife angle. Surface roughness, rotation, heat transfer, and coolant flow injection are also input variables. Modifications were made to the program to simplify input and output for user friendly operation.

The user's manual for the labyrinth seal analysis code is presented in Volume II (67). The analysis program has been compiled for the CDC and Cray I computers.

The "design" model development, presented in this volume, is based on detailed knife-to-knife (KfK) flow analysis which uses empirical corrections to a simplified one-dimensional theory. The empirical corrections for seal geometric effects are based on statistical analyses of generalized experimental performance. The "design" model is capable of predicting the leakage for a wide range of straight, stepped, and mixed straight and stepped seal configurations. In addition, the "design" model has the capability to optimize a seal configuration within specified geometrical constraints such as clearance, axial envelope, inlet air temperature, and overall pressure ratio. The user's manual for the labyrinth seal design code is presented in Volume IV (68).

Rig tests were performed on selected full-scale labyrinth seal configurations to extend the data base and provide verification for the "design" model. A test program devoted to the characterization of straight and stepped seal performance with a variety of open-cell honeycomb lands was run statically and

*Numbers in ( ) refer to References, page 148.

dynamically in the three-dimensional (3-D) test rig. Large-scale seal models were tested in the Allison two-dimensional (2-D) seal test rig to obtain leakage performance, intraseal pressures and temperatures, velocity distributions, and flow field visualization for "analytical" model verification.

This volume is devoted to the presentation of results from the literature survey, development of the empirical "design" model, and supporting experimental data.

2.0 SUMMARY

The Design Model development program was started with a literature search to identify significant geometric and aerodynamic parameters that influence leakage, to determine the most useful theoretical approaches to predicting labyrinth seal performance, and to acquire a data base upon which to develop an advanced empirical model.

The knife-to-knife approach to modeling labyrinth seal performance was selected as the most promising technique to achieve flexibility and accuracy. Using an empirical building block procedure, a three element loss model was formulated for a single knife and extended to include multi-knife straight seals and stepped seals. A statistical analysis was employed with the performance data base to derive loss correlations for contraction, expansion, and venturi and friction. These correlations were derived not only to produce a good data match, but to provide physical realism to the loss process. The resulting knife-to-knife (KTK) seal design model demonstrated an accuracy of $\pm 5\%$ in the prediction of leakage flows for the data base configurations which include straight and stepped seals with vertical or slanted knives.

A seal design optimization routine was developed for the KTK Design Model. With this capability, a minimum leakage seal configuration can be identified for a specific engine application, e.g., design constraints on clearance, axial envelope, inlet air temperature, and overall pressure ratio.

Performance data were acquired by testing specific labyrinth seals to fill voids in the KTK model data base obtained from the literature search and existing Allison data. Twenty-three tests on straight seals (12 tests) and stepped seals (11 tests) were conducted to extend experimental coverage on the effects of knife angle, tip thickness, pitch, height, number of knives, and land surface roughness. This entire data base was utilized in the development of the Allison Design Model.

Flow visualization studies were conducted to provide qualitative data upon which to identify loss mechanisms and to verify flow phenomena calculated with the Analysis Model (66). These tests were conducted in the 2-D static rig using large-scale seal hardware with a schlieren flow visualization technique. A total of nineteen tests were performed on straight seals, and six tests were conducted on stepped seals. Valuable insights were obtained about the conformation of flow fields through single knife and multiple knife seals. The flow perturbations introduced by knife edge rounding, knife slanting, knife spacing, and clearance change were observed. Although some still pictures were acquired, the motion on the video tapes provided the most definitive description of the internal flow characteristics. These visualization experiments provided good qualitative verification of the Analysis Model and aided in the corroboration of loss mechamisms for the Design Model development.

Five performance tests were conducted on large-scale (ten times size) straight seals to provide quantitative comparisons of seal leakage characteristics with the Analysis Model. Four large-scale tests (at five times full-scale) were performed with stepped seals. These tests were done on the large-scale flow visualization models in the 2-D static rig. Measurements of static pressure and total temperature were made at selected points in the intraseal flow passage. A comparison with an approximate analytical equation for labyrinth seal pressure gradient derived by Kearton and Keh (31) showed good agreement with the exception of the first knife which seems to provide a larger than anticipated pressure drop. As the overall seal pressure ratio increases, the acceleration to the last knife becomes more pronounced until choking occurs. The jet from the last knife appears to behave in the same way as the discharge from a convergent, annular nozzle with an extensive base recirculation region.

Detailed velocity surveys were made on the three knife straight and stepped seal models with the tapered large-scale knives using LDV and hot wire measurement techniques. Velocity distributions measured in front of the first knife, in the clearance gaps, and in the cavities between knives provided good qualitative agreement with the Analysis Model. The hot wire measurements produced better resolution of the velocity profiles than the LDV due to the proportionately large spot size of the LDV beam. The LDV data appeared to be dampened due to "smearing" of the velocity gradient through the spot. Local distortions of the flow field were incurred at the seal land due to the access holes for entry of the hot wire probe. A redesign incorporating a reduced slot size provided substantial improvement in the accuracy of velocity profile data. The integrated velocity profiles in the clearance gaps of the straight seal and the stepped seal agreed well with the mass flowrates measured downstream of the rig.

Additional full-scale performance testing was conducted to extend the labyrinth seal data base to evaluate the effect of interknife cavity aspect ratio (KP/KH) and the interaction with clearance. A total of eighteen tests were made on vertical knife straight seals with interknife cavity aspect ratios from 0.40 to 4.0 at three clearance values. The results of these tests confirmed the optimum performance of a square (KP = KH) interknife cavity for the knife geometry utilized. The Design Model predicts the performance of straight seals very well at knife tip clearances of 0.010 in. or greater when interknife cavity aspect ratio is 1.0 or larger. However, significant overpredictions of leakage can occur for straight seals with short or deep interknife cavities (KP < KH) or with clearances near 0.005 in. The uncertainties associated with full-scale model testing at small parametric dimensions are suspected as the cause of the data dispersion which is the source of the modeling problem.

Wide-spread usage of open-cell honeycomb lands over the last ten years prompted an experimental effort to quantify the effects of honeycomb on seal performance. Thirty-eight tests, using the 3-D dynamic rig, were conducted on a five knife straight seal (30 tests) and on a four knife stepped seal (8 tests) with three honeycomb cell sizes. The effect of knife slant angle was investigated statically and dynamically to 785 ft/sec knife tip speed. The data supported earlier indications (54) that open-cell honeycomb lands could be beneficial or detrimental to the performance of multiple knife straight seals. As expected, the smaller honeycomb cell size tends to more closely follow solid land performance characteristics, but the leakage is strongly affected by the ratio of cell size to clearance. In general, honeycomb cell sizes of 0.031 in. and larger are detrimental to straight seal performance at clearances less than 0.010 in. A reduction in leakage as compared with a solid-smooth land was noted for honeycomb cell size to 0.125 in. at a clearance of 0.020 in. A significant rise in the temperature of the air leaking through the seals with honeycomb lands is associated with the increased pumping work required to swirl the flow past the honeycomb.

Eight tests were performed to evaluate the effect of honeycomb on stepped seal performance. In all cases, the application of honeycomb resulted in a large increase in leakage relative to the solid-smooth land.

During this Labyrinth Seal Analysis program an extensive bibliography and a large performance data base have been compiled. The KTK Design Model was derived from this data base. The evaluation tests vindicated the selection of three element loss correlations for the KTK flow analysis. The Design Model provides an improved performance prediction capability applicable to a wide range of seal geometric and aerodynamic parameters. The use of an optimization algorithm with the KTK performance model enables the selection of the seal configuration which will leak the least for an arbitrary set of design constraints.

3.0 LITERATURE SURVEY

A literature survey was conducted to identify the most successful theoretical approaches to modeling labyrinth seal performance and to obtain "outside" experimental data on conventional labyrinth seals. Citations of books, reports, technical papers, and articles relating to labyrinth seal technology were found through automated literature searches and reviews of NTIS Government Report Announcements. A detailed discussion of the literature search can be found in the interim report (65).

3.1 ANALYTICAL MODELS

The reference evaluations (64) revealed certain general areas of agreement among past and present researchers as well as some points of disagreement or departure.

The leakage through a labyrinth seal is invariably modeled as an adiabatic throttling process. Gas phase and vapor phase working fluids have been described with the thermally perfect equation of state and calorically perfect thermodynamic assumptions with apparently good results. The neglect of real gas and heat transfer effects evidently is of secondary importance to most labyrinth seal applications. The thermodynamic model for the series-of-throttles process ideally predicted for labyrinth seal leakage is illustrated as shown in Figure 1.

The ideal throttling model has led to two schools of analytical representation for labyrinth seal performance calculations. The most widely employed assumption treats the labyrinth seal as a series of discrete restrictions with associated local pressure losses. However, another model characterizes the labyrinth seal as a rough pipe with uniformly distributed wall friction. The general opinion of most researchers seems to support the series-of-restrictions model as having a more physically realistic formulation with the attendant ability to develop the pressure loss components on a rational geometric and parametric basis. The rough pipe model seems to rely more heavily on purely

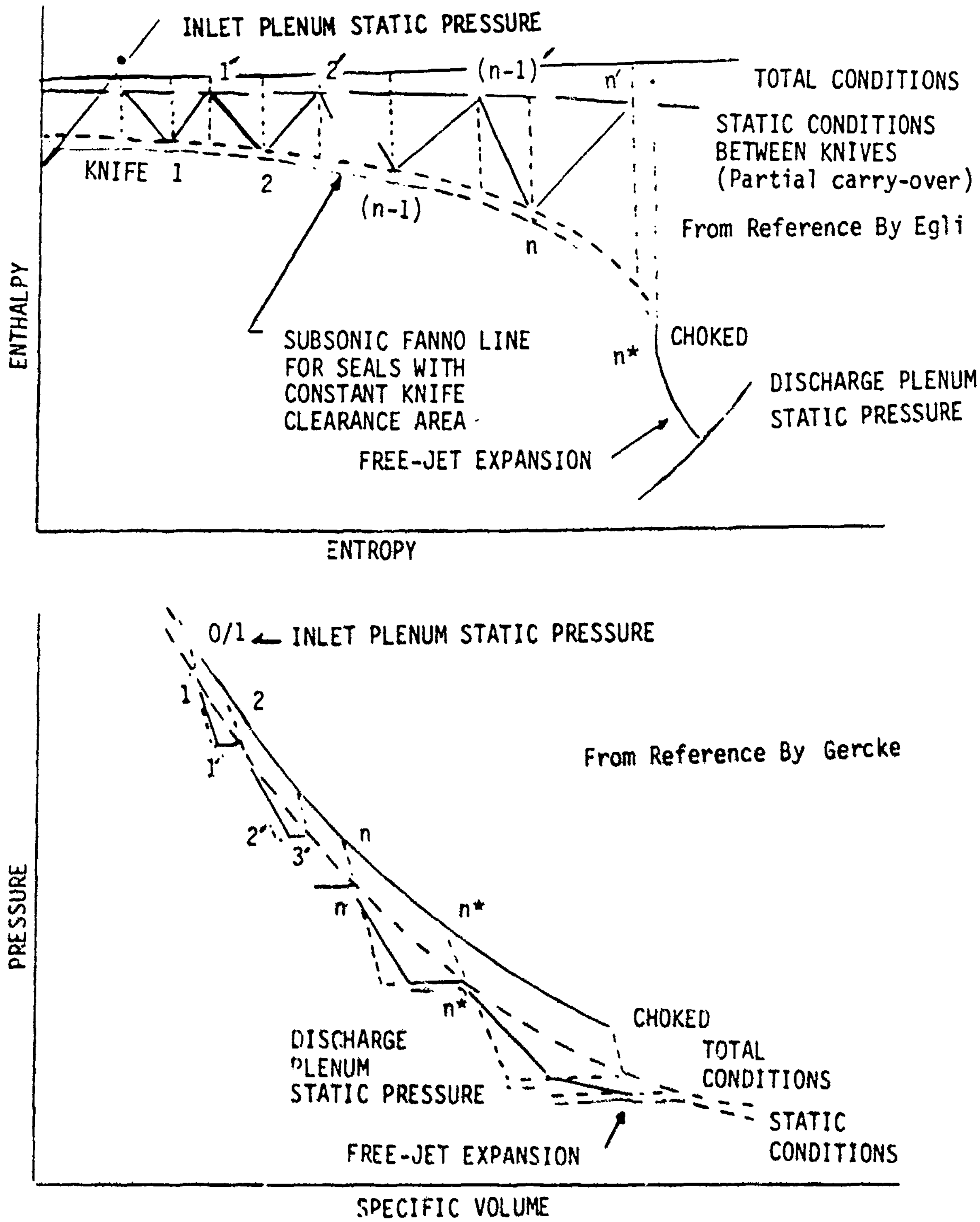

Figure 1. Thermodynamic processes for labyrinth seal leakage.

empirical correlations to predict the equivalent wall friction. However, very little difference in model accuracy, current or potential, could be found.

Several survey papers on labyrinth seals were utilized to assist the literature search. Those discussions cited in Ref 3, 5, 8, 19, 39, 51, and 57 elaborate on the series-of-restrictions models and the rough pipe models.

3.1.1 Rough Pipe Global Model

The rough pipe model assumes that the leakage through a labyrinth seal is analogous to the compressible flow through a duct with uniformly distributed roughness. Under these assumptions the resulting labyrinth seal model becomes global in the sense that no mechanistic analysis of the internal flow is required. The early Fanno line analysis concepts of Becker (6) were extended by Trutnovsky (57) where the pressure drop characteristics of the seal were related to an equivalent wall roughness, 4f, of the basic seal channel which is characterized by ℓ/H. This concept was simplified and elaborated on by Zabriskie and Sternlicht (61) who correlated the equivalent wall roughness parameter with certain seal geometry characteristics and a Reynolds number parameter. The mathematical formulation and data correlation of the labyrinth seal performance based on equivalent roughness friction factor can evidently be carried out with accuracies equivalent to those achieved with the series-of-restrictions models. However, the lack of physical relevance of the roughness friction factor limits the use by the designer.

3.1.2 Series-of-Restrictions Global Model

The series-of-restrictions model assumes that leakage through a labyrinth seal is governed by the local character of the sequential accelerations and decelerations experienced as the fluid passes through the clearance gaps at the knives. The earliest analyses based on this model postulated the total annihilation of the dynamic pressure after each knife, i.e., complete thermodynamic reheat, to derive a global equation of the form,

$$\phi = C_D \Gamma \sqrt{\frac{1 - r^2}{KN - a \ln r}}$$

The value of a results from the local thermodynamic restrictions imposed upon the model derivation. For seal leakage limited to the incompressible flow regime, $a = 0$ (10 and 55). When the flow regime is considered compressible, the $a = 1$ for local isothermal processes (17 and 41) and $a = 2/\gamma$ for local isentropic processes (18).

The theoretical derivation of the global equation is postulated on equal effective areas for each clearance gap. This assumption is approximately true for axial, straight, or staggered seals with constant clearance. Then the primary deviation is attributable to compressibility effects, $C_{Dn} = f(Pn/Pn+1)$. For stepped seals and, more dramatically, for radially oriented seals of any type, the constant effective area assumption leads to erroneous leakage predictions. However, these geometrical contributions to area variation can be accounted for analytically (42) with some additional formulation complication proposed by Gercke (21).

The global model assumption that contributes the greatest deviation from the real physics of straight-seal leakage is the assumption of no velocity carry-over, $\Gamma = 1.0$. The residual velocity in jets encountering downstream knives can significantly increase the leakage through straight seals (18). A variety of analytical correction factors (26, 58, and 60) and empirical correction factors (18 and 25) have been proposed to account for this global model deficiency.

3.1.3 Knife-to-knife Model

All global models (both series-of-restrictions and rough pipe approaches) encounter difficulties with supercritical seal operation (45). A supplementary and necessarily approximate model for the choking pressure ratio is required (31, 40, and 55). Also, the global models do not treat the variation of knife discharge coefficient and velocity carry-over realistically with respect to the pressure ratios through the seal (43). The accurate treatment of clearance area changes and other nonconstant geometrical parameters is difficult at best (32) and is frequently impossible. The routine use of large, high-speed digital computers for engineering design makes the basic knife-to-knife analysis of individual labyrinth seal designs feasible from the standpoint of time and effort and desirable for flexibility, comprehensiveness, and accuracy. In the knife-to-knife approach, the one-dimensional flow parameters in the knife throats are computed and linked together by a total pressure loss calculation. Usually, a flow coefficient is utilized to account for the vena contracta in the knife throat. Each knife may have an individual flow coefficient value, or groups of knives may have one value and the last knife another. Carryover of the velocity head in a straight seal is considered by taking only a partial velocity head loss in total pressure between knives. Komotori (37) utilized an expansion angle to determine the fraction of velocity head lost.

Callendar (10) performed an early knife-to-knife analysis using the isentropic St. Venant-Wantzel flow equation with adiabatic throttling process constraints to evaluate the accuracy of the global equations of Stodola and Martin. Egli (18) later utilized the same technique to extend his flow curves to include small numbers of knives (effectively $1 \leq KN \leq 4$). Recent researchers have extended and refined the knife-to-knife model until it is unquestionably the most versatile and precise labyrinth seal design model.

Since Koenig and Bowley (34) demonstrated the versatility of the knife-to-knife model using the compressible flow equation of St. Venant and Wantzel with the seal performance data of Egli (18) coded for digital computer, a series of similar but increasingly complicated knife-to-knife models have been proposed.

The knife-to-knife seal models of Komotori and Mori (36) are by far the most sophisticated and versatile proposed to date. The models are broadly based on the adiabatic character of the fluid flow through a series of throttles. However, the applicability to seal leakage involving heat transfer has been demonstrated experimentally. These data indicated a very weak effect of heat transfer on leakage magnitude. The flow through each knife gap is calculated with the St. Venant-Wantzel equation for isentropic flow corrected by an empirical discharge coefficient. Downstream expansion losses are assumed complete for staggered and stepped seals. However, the velocity carry-over effects for straight seals are modeled as a sudden expansion pressure loss from Borda's equation. The expansion ratio is obtained from a constant jet expansion angle which was derived from test data and the geometrical characteristics of the seal knife pitch and clearance. This straight seal model was empirically extended by Komotori and Miyake (37) to account for the effects of knife rotation on leakage.

A similar knife-to-knife approach was derived by Hawas and Muneer (24). A correction was added to the single knife discharge coefficient for the influence of downstream knives. Also, an empirical correction for velocity carry-over in straight seals was substituted for the theoretical Borda equation.

The results of the evaluation of the surveyed labyrinth seal performance models which have been proposed in the literature indicate that the global models are no longer sufficiently versatile or accurate for the analysis, design, and optimization of modern labyrinth seals. The knife-to-knife models with physically appropriate empirical corrections appear to offer the greatest potential for the accurate calculation of seal performance.

3.2 AERODYNAMIC PARAMETERS

The aerodynamic parameters which specify labyrinth seal performance on a dimensionless, generalized basis are given in Table 1. The labyrinth seal performance is conventionally expressed in terms of the dimensionless mass flowrate parameter as a function of overall seal pressure ratio. Frequently, the mass flowrate parameter is expressed dimensionally, but with almost as much generality, as $\phi = w\sqrt{T_U}/P_U A_t$ ($lb_m\ {}^\circ R^{1/2}/lb_f$ sec), and the reciprocal of the pressure ratio, r, is used to obtain a finite range of that parameter, 0 to 1.0. Perry (46) demonstrated the facility of elliptical coordinates, ϕ^2 versus $(1-r^2)$, in linearizing orifice flow data. Inspection of Stodola's global formula for labyrinth seal leakage supports the efficacy of elliptical coordinates for the presentation of labyrinth seal performance.

Table 1.

Aerodynamic parameters for labyrinth seals.*

Parameter	Symbol	Function	Effect
Mass Flowrate	ϕ	$w\sqrt{RT_U}/\sqrt{g_c}\ P_U A_t$	Dependent variable
Pressure Ratio	P_R	P_U / P_D	Strong
Axial Reynolds Number	Re	$(w/A_t)\ 2CL/\mu_U$	Moderate
Knife tip speed	V_{corr}	$V/\sqrt{g_c RT_U}$	Moderate
Rotational Reynolds Number	Re_N	$P_U\ \omega^2/\mu_U R\ T_U$	Weak
Taylor Number	Ta	$(P_U V\ CL/\mu_U RT_U)\sqrt{CL/r_K}$	Weak

*See seal nomenclature and list of symbols.

The axial Reynolds number influences the discharge coefficients for the seal knives, but its effect on overall seal performance has not been established experimentally. The axial Reynolds number, which is constant for a specific seal operating at a given pressure ratio with the exception of very slight temperature and pressure effects on viscosity, has been found by Wittig, Dorr, and Kim (63) to affect the performance of similar seals of different sizes.

Rotor angular velocity affects seal performance at high knife tip speeds, but the characteristic is strongly perturbed by seal geometry and land surface conditions in a presently undetermined manner (37). Similarly the effect of rotational Reynolds number is unknown but may be involved with the knife tip speed effects observed. Taylor number has no significant effect on the leakage past cylinders rotating relative to one another, although it has a strong effect on heat transfer. However, its influence on the labyrinth seal leakage has not been investigated. Intuitively, the effect of Taylor number, which is the product of a Reynolds number and CL/r_K, would seem to be insignificant based on the excellent agreement between 2-D rig and 3-D rig test results. Since curvature (CL/r_K) appears to have little if any effect on the performance, all of the influence could be ascribed to rotational Reynolds number alone. The present dearth of reliable test data and the divergent opinions of many researchers on the importance of rotational effects would make modeling of the knife tip speed, rotational Reynolds number, and Taylor number effects highly speculative and unreliable.

3.3 GEOMETRIC PARAMETERS

The seal geometry parameters which specify labyrinth seal performance can be expressed in terms of geometrical similarity criteria compatible with the generalized aerodynamic performance parameters (8). The strongest geometrical variable affecting seal leakage is the clearance between the knife tip and the land surface (CL), which defines the throttling area (A_t). Therefore, the seal clearance is the best basis for establishing geometrical similarity in labyrinth seal design. A list of the geometric parameters for conventional straight and stepped labyrinth seals is given in Table 2. The classification by influence of the geometric parameters in Table 2 is based on the empirical evidence accumulated from the test results and opinions of many researchers reviewed during the literature survey.

The strong effect of the number of knives was recognized in the earliest analyses of labyrinth seal performance. Knife angle influence was not considered until later, after the separate effects of stream contraction due to orifice geometry and stream velocity distribution due to Reynolds number were observed.

The importance of relative knife tip thickness on the discharge coefficient was determined by Egli (18). Trutnovsky (57) reported on the investigation by Troyanovski of the influence of knife blade shape and knife tip sharpness. The effect of leading-edge rounding on discharge coefficient was quantified. Jackson (28) showed that the back face geometry of the knife could affect carry-over. Relative knife pitch, KP/CL, was used by Jones (30) to correlate the performance of straight seals in the practical range of relative knife tip thickness, KT/CL. Stocker (54) showed that some optimization of KP/CL was possible in stepped seals. Abramovich (1) contends that relative knife height

Table 2.
Geometric parameters for labyrinth seals.*

Parameter	Symbol	Functional	Influence Straight	Influence Stepped
Number of knives	KN	Number of throttles	Strong	Strong
Knife angle	$K\theta$	Orifice geometry	Moderate	Moderate
Knife tip thickness	$\frac{KT}{CL}$	Relative throat length	Moderate	Moderate
Knife tip sharpness	$\frac{r_t}{CL}$	knife relative sharpness	Moderate	Moderate
Knife blade shape	parallelogram tapered, etc	Orifice geometry	Weak to Moderate	Weak
Knife pitch	$\frac{KP}{CL}$	Relative throttle spacing	Moderate	Weak
Knife height	$\frac{KH}{CL}$	Relative chamber depth	Weak	Weak
Land surface roughness	$\frac{\varepsilon}{2CL}$	Land relative roughness	Moderate	Weak
Land surface porosity	$\frac{Pb}{CL}$	Land relative porosity	Moderate	Weak to Moderate
Step height	$\frac{SH}{CL}$	Relative step height	-	Weak
Distance to contact	$\frac{DTC}{CL}$	Rotor relative axial location	-	Weak to Moderate
Flow direction	STLD LTSD	Flow down the stator step Flow up the stator step	-	Weak

*See nomenclature and list of symbols.

has a weak influence on straight seal performance until the labyrinth cavity becomes so shallow that the through-flow jet expansion fills the cross-section. Then the sudden compression of the stream which occurs at the downstream knife is controlled by the relative knife height geometry. Testing by Stocker (54) indicated a weak effect of relative knife height on stepped seals, also.

Stocker (54) also initiated some investigation of the effects of land surface roughness and porosity on seal performance. Surface roughness was shown to have a limited range of benefit, but porosity always has a detrimental effect on seal leakage. Most investigators have accepted the hypothesis that the tortuosity of the step geometry results in nearly complete destruction of the carry-over velocity. However, experiments by Stocker (54) have demonstrated a weak but surprising optimization for relative step height. Distance to contact and flow direction were also shown to have a usually small but measurable effect on seal performance by Stocker (53) and Cox (14).

3.4 LABYRINTH SEAL PERFORMANCE DATA BASE

The data base of labyrinth seal performance was established by a careful screening process. All applicable sources of experimental seal data identified in the literature survey were examined to see if the tests yielded accurate results and if all pertinent geometric and aerodynamic parameters were reported. In some cases, authors were contacted to obtain additional information. Data deemed satisfactory were digitized electronically, converted to flow factor versus pressure ratio and plotted. These plots were reviewed to eliminate apparent bad data by identifying specific points or curves in obvious disagreement with the majority of the data.

Data which passed the screening process were placed in a computer data file. The file contained the performance test data points (ϕ versus pressure ratio) and corresponding seal geometric parameter values. This file then became the data base for the Allison Design Model discussed in Section 4.0.

Table 3 summarizes the sources, seal types, and quantities of performance data in the data base. A configuration represents a set of test data points for a given seal geometry. Data were included for 175 different single-knife seal, straight seal, and stepped seal configurations. The number of data points per configuration varied from 1 to 54 yielding a total of 1839 test points in the data base. Table 4 lists the ranges of the geometric parameters covered in the data base.

Tables 3 and 4 show that the data base used to build the Design Model is extensive and covers a wide range of parameter values. The data come from a diversity of sources with 40% of the configurations tested at Allison under various contracts including this AFAPL contract.

3.5 DESIGN MODEL CANDIDATES

The literature survey yielded several potentially useful performance prediction models for labyrinth seals as summarized in Table 5. Six models were coded for computer solution. Five models were global types: Egli, Allison Design Manual (similar to Egli), Jones, Martin and Stodola. One model was chosen to represent the knife-to-knife analyses, i.e., Hawas and Muneer. The global model type refers to the approach of treating an entire seal, rather than the sequence of individual internal component geometries, as a means of estimating leakage. A comparison of the predictions from the models with test data for a typical seal configuration in the data base is given in Figure 2. The model predictions deviate from the test data by as much as -17% to +38%, indicating the wide range of results which can be calculated from models available in the literature. Additional comparisons of the three global models based on performance maps, i.e., Egli, Jones, and the Allison Design Manual, have been made with test data for 38 of the straight seal configurations in the data base. The performance map model type uses input plots of flow function versus geometric variables to obtain leakage rates. Deviations were found to range from -22% to +76%, again demonstrating the inadequacy of available models to accurately predict seal performance for a variety of geometric designs.

Table 3.
Labyrinth seal Design Model data base.

	Number of seal configurations			
	Single knife	Straight	Stepped	Total
Kearton and Keh (31)	3	0	0	3
Caunce and Everitt (13)	6	4	46	56
Meyer and Lowrie (43)	10	0	0	10
Komotori and Miyake (37)	1	12	0	13
Harrison (23)	0	13	10	23
Allison (14), (53), (54) (IR&D), and (AFAPL contract)	8	29	33	70
Total No. Configurations	28	58	89	175
Total No. Test Points	373	779	687	1839

Table 4.
Parameter ranges in the labyrinth seal Design Model data base.

		Seal type			
				Stepped seal	
Parameter		Single knife	Straight seal	STLD dir.	LTSD dir.
KN	min	1	2	2	2
	max	1	12	6	6
KT/CL	min		0.21	0.21	0.50
	max	3.3	4.4	2.64	1.50
Kθ	min	30	60	50	50
	max	90	90	90	90
KH/CL	min	-	2.7	5.1	5.1
	max	-	31.3	29.4	28.0
KP/CL	min	-	4.0	6.4	9.2
	max	-	56.3	53	40
ε/(2CL)	min	0	0	0	0
	max	0	0.030	0	0.030
SH/CL	min	-	-	2.0	4.0
	max	-	-	29.4	12.5
DTC/CL	min	-	-	0.85	4.1
	max	-	-	40	19.4
(KP-KT)/CL	min	-	3.5	6.2	8.9
	max	-	55.0	51.8	38.5

Table 5.
Design model types reported in the literature.

Modeling Approach	Global (Control Volume)			Knife-to-Knife
Analysis Method	Formula	Friction Factor	Performance Maps	Fluid Mechanical
Authors	Martin Stodola Dollin & Brown Gercke Bartosh Scheel Vermes	Becker Trutnovsky Zabriskie & Sternlicht	Egli Jones Myer & Lowrie Heffner Allison Design Manual	Morrow Robinson Idel'chik Abramovitch Koenig & Bowley Komotori Hawas & Muneer Benvenuti, et.al.
Applicability	Simple	Difficult to complex	Moderately difficult	Complex. Good fluid mechanical concept of losses.
Solution	Manual computation	Manual or computer computation	Manual or computer computation	Computer computation
Disadvantages	Difficult to apply carry-over corrections & knife-to-knife flow coefficient variations.	Requires extensive friction factor or flow coefficient data. Lacks physical significance.	Requires extensive overall correlations for flow coefficient & carry-over factor.	Requires extensive models of knife throat & cavity fluid dynamics.

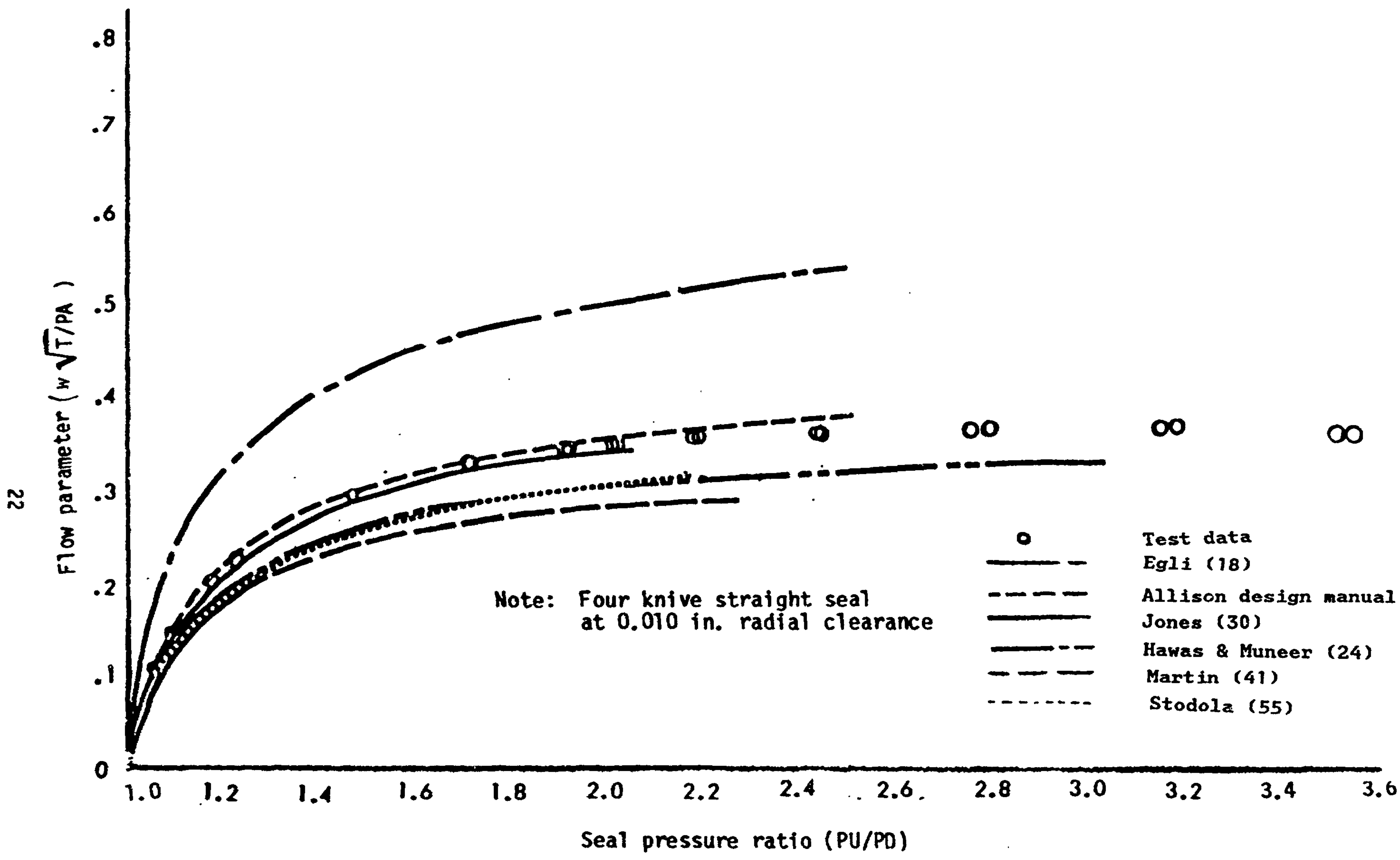

Figure 2. Comparison of labyrinth seal performance models with test data.

One approach to developing a design model is simply to correct the candidate model(s) with a multiplying factor. The factor in general would be a function of the geometric parameters. This approach was pursued by calculating the multiplying factor from the model-test data deviations, i.e., ratio of test flow factor to calculated value, and correlating the result as a function of the geometric parameters. A linear regression analysis for several models for both straight and stepped seals was used to obtain the correlation. The results showed that the modified models could predict the seal performance within ±7% mean deviation.

Using an overall correction factor approach on any existing model is simple to implement and would give reasonably accurate results for the data ranges considered. However, such models would not lend themselves to extrapolation because the terms in the correlations would, in general, not be physically relevant.

Based on the review of various candidate model approaches for considering the flow in labyrinth seals, a knife-to-knife (KTK) analysis was selected as a starting point for the Design Model in this program. The KTK approach provides:

- o the most physically realistic formulation of the knife throat and cavity fluid dynamics in terms of geometric parameters,
- o interknife pressure information,
- o a versatile tool with growth potential to include additional parameters and/or extended parameter ranges.

4.0 LABYRINTH SEAL DESIGN ANALYSIS

The labyrinth seal Design Model developed by Allison is based on the knife-to-knife (KTK) flow analysis approach. The losses at each knife have been separated into the following three dynamical mechanisms as shown in Figure 3:

- o contraction--stations 1 to 2 and 4 to 5,
- o venturi and wall friction--stations 2 to 3 and 5 to 6,
- o full or partial expansion--stations 3 to 4 and 6 to 7.

The three loss coefficients can be related to the geometric and aerodynamic seal parameters in a physically realistic way. Consequently, the chosen knife-to-knife model is potentially more flexible and accurate than a global (control volume) model which uses overall flow coefficients or a KTK model that employs a single discharge coefficient for each knife.

4.1 MODEL FORMULATION

The design model is based on:

- o a one-dimensional representation of a locally adiabatic flow which may be piecewise diabatic,
- o the calculation of three individual loss coefficients at each knife from flow and geometric conditions,
- o the modification of the loss coefficient values due to the position of the knife in the seal (presence of adjacent knives),
- o a sequential solution for the pressure distribution in the seal from the dynamics of the flow through the series of knife throttles.

Table 6 presents the parameters which were selected for incorporation into the Design Model. The parameter selection was based on the results of the literature survey and previous Allison experience. These parameters, which govern labyrinth seal performance, are illustrated in Figure 4. The more complex seal geometries are defined in the nomenclature of labyrinth seal geometry.

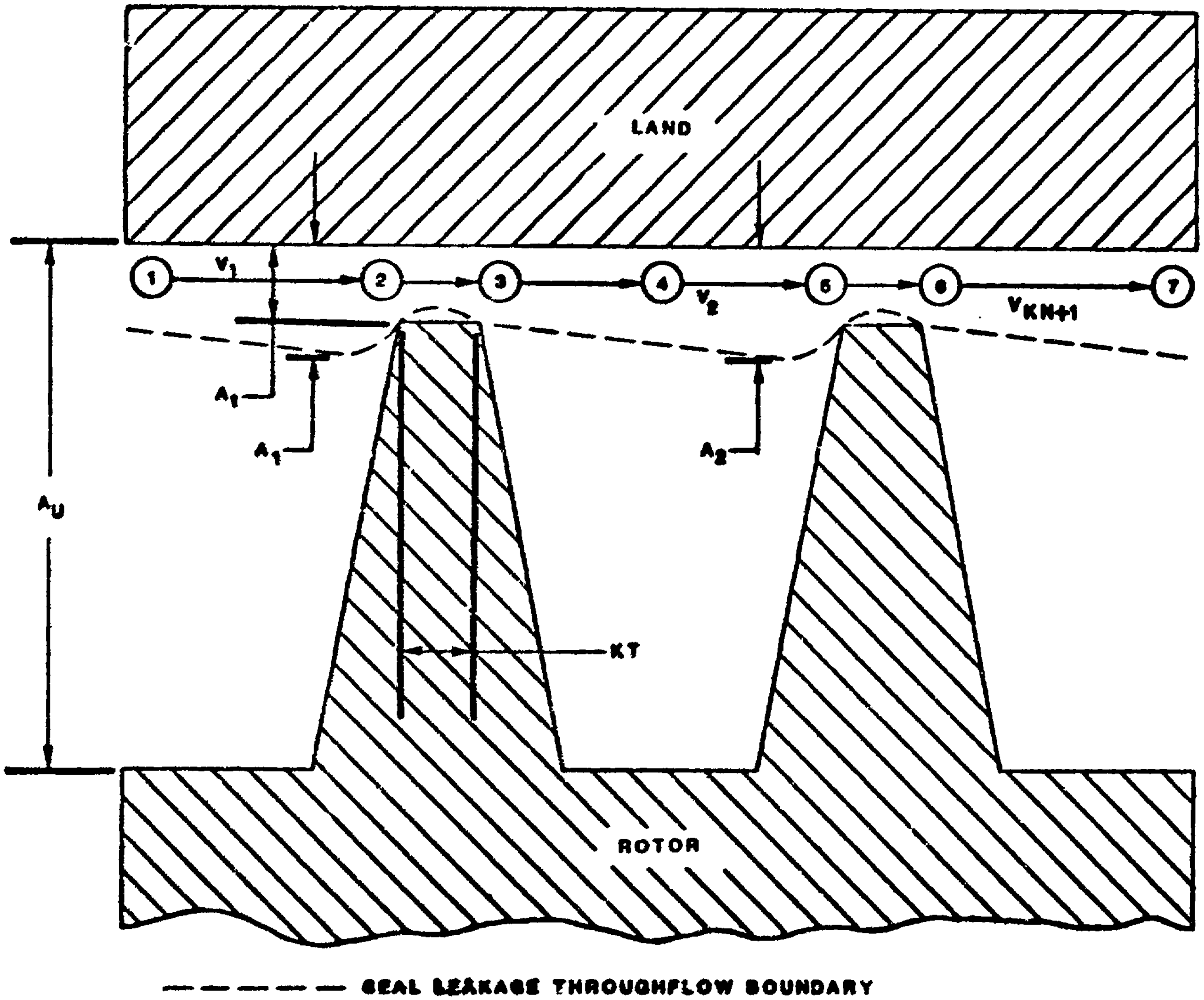

Figure 3. Seal loss zone schematic.

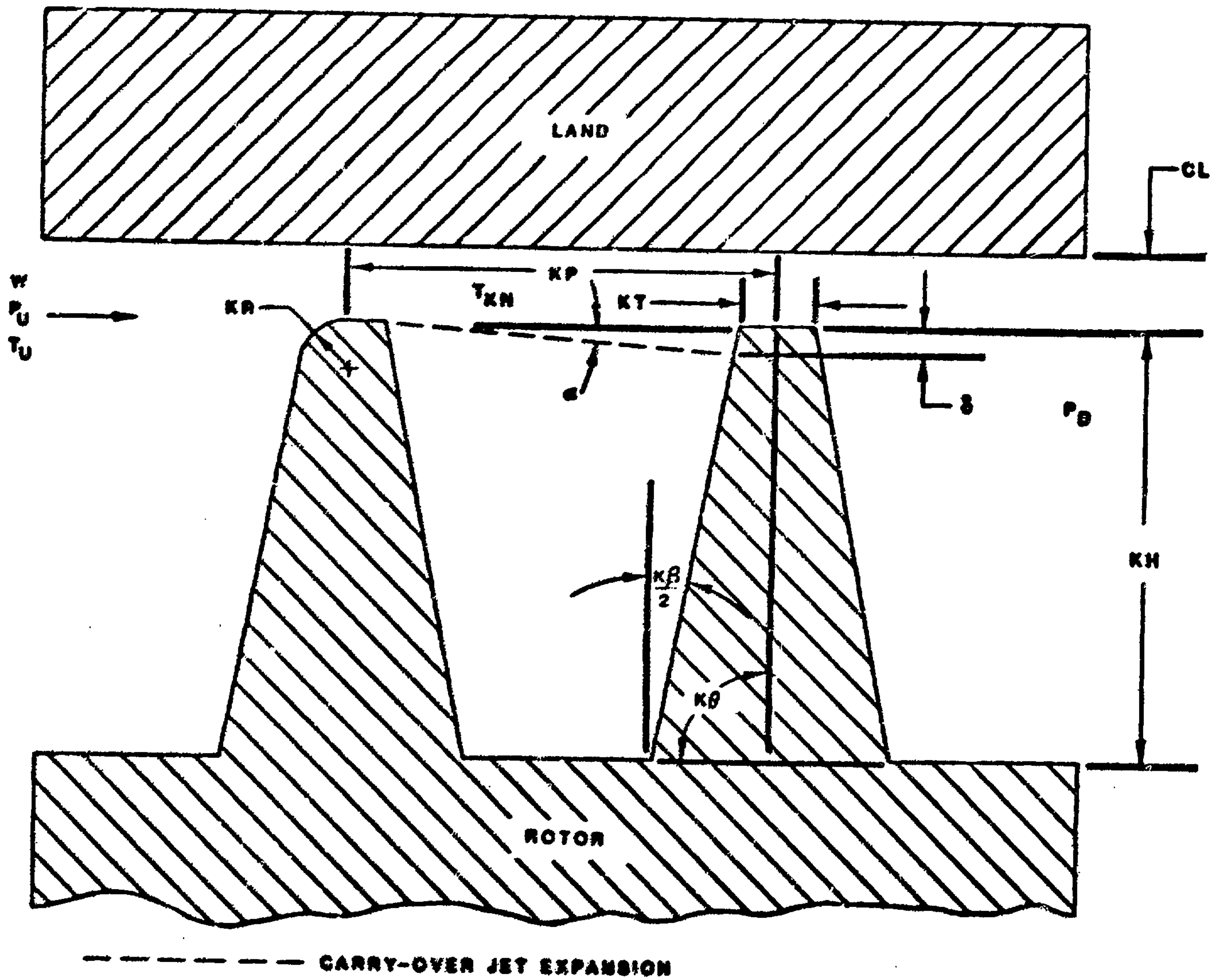

Figure 4. Labyrinth seal schematic illustrating the governing paramaeters for a vertical knife straight seal.

Table 6.

Parameters in the Design Model

Geometric parameters for straight and stepped seals

- o Knife height (KH)
- o Knife pitch (KP)
- o Number of knives (KN)
- o Knife angle (Kθ)
- o Knife tip thickness (KT)
- o Knife taper angle (Kβ)
- o Knife tip leading edge radius (KR)
- o Clearance (CL)
- o Surface roughness (ϵ)

Additional parameters considered for stepped seals

- o Step height (SH)
- o Distance to contact (DTC)
- o Flow direction (LTSD or STLD)

Flow parameters

- o Overall pressure ratio (P_U/P_D)
- o Inlet stagnation pressure (P_U)
- o Fluid temperature distribution (T_Z)
- o Flow rate (w)

All local flowstation conditions were assumed to be adiabatic so that the compressible flowrate could be calculated from the Saint Venant-Wantzel equation.

$$\phi = \sqrt{\frac{2g_c\gamma}{R(\gamma - 1)}}\left(\frac{P_s}{P_t}\right)^{\frac{1}{\gamma}}\sqrt{1 - \left(\frac{P_s}{P_t}\right)^{\frac{\gamma-1}{\gamma}}} \qquad 4.1$$

Using the isentropic relationship between total and static pressure,

$$\frac{P_t}{P_s} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \qquad 4.2$$

the mass flowrate parameter can be expressed in terms of the local Mach number,

$$\phi = \sqrt{\frac{g_c \gamma}{R}} \quad \frac{M}{\left(1 + \frac{\gamma - 1}{2} \; M^2\right)^{\frac{\gamma + 1}{2(\gamma - 1)}}} \qquad 4.3$$

The dynamic loss in total pressure between any two stations can be expressed by using the appropriate equation in the three element loss model,

$$\Delta P_t = K_c \frac{\gamma}{2} P_s M^2 \qquad \text{contraction loss} \qquad 4.4$$

$$\Delta P_t = K_{vf} \frac{\gamma}{2} \; P_s \; M^2 \qquad \text{venturi and friction loss} \qquad 4.5$$

$$\Delta P_t = K_e \; (P_t - P_s) \qquad \text{expansion loss} \qquad 4.6$$

The loss coefficients are based on the isentropic flow conditions in the smaller of the channel areas at the seal station. Equations 4.3 through 4.6 define the flow characteristic through the seal as a function of seal pressure ratio. An iterative solution is employed that assumes the mass flowrate until the specified seal pressure ratio is matched. The contraction loss, venturi and friction loss, and expansion loss are computed in the sequence of flow for each knife in series. Corrections are applied to the baseline single-knife loss coefficients to adjust for the effects of adjacent knives.

A building block approach was used to derive the loss coefficient correlations. Starting with the single-knife performance, the loss coefficients were correlated against the independent seal parameters with a multiple regression analysis. Physically relevant candidate equations were chosen on the basis of limit analysis. The applicability of the candidate equations was examined by comparing their predictive capability against the labyrinth seal performance data base. The equations which produced the best overall data match were selected to model each of the three baseline loss coefficients. Then these single-knife seal performance correlations were extended to include multiple knives in straight seal and stepped seal configurations by applying a similar regression analysis and data matching procedure.

4.2 SINGLE-KNIFE SEAL MODEL

The correlation of single-knife data affords the advantage of basic loss phenomena evaluation without the complicating influence of adjacent knives. The available single-knife data were analyzed for the purpose of characterizing the contraction loss (K_c) and venturi loss with wall friction (K_{vf}).

The expansion losses (K_e) incurred for the single-knife seals were nearly equal to the entire difference between the total and static pressures at the throttle discharge due to the very large downstream channel areas relative to the clearance gap areas. Therefore, the expansion loss coefficient was specified as unity, $K_e = 1.0$.

Due to the large area variation between the inlet channel and the clearance gap, the flow into the knife throat is analogous to that into a sharp-edged orifice. Here the radius on the leading edge of the knife is the primary parameter affecting the contraction loss. Using the single-knife data of Kearton and Keh (31) in which the knife exhibited a very sharp leading edge, a K_c value of 0.7 was found when the venturi loss was assumed to be independent of the leading edge radius.

With the contraction loss established, the characteristic of the venturi loss can be determined as a function of relative knife tip thickness (KT/CL) and land wall roughness (ϵ/2CL). The single-knife seals had aerodynamically smooth lands so that the relationship between knife tip thickness and venturi loss could be found directly, Figure 5. The correlation of K_{vf} with flow parameter is equivalent to expressing K_{vf} as a function of the Mach number over the knife. A relatively sharp knife (small KT/CL) has a strong influence on the pressure drop at low Mach numbers, but becomes less effective as the pressure ratio increases.

Additional sources of single-knife seal data were utilized to establish the effect of the knife leading edge sharpness on single-knife performance. The linear regression analysis of these data resulted in the functional relationship for contraction loss coefficient (K_c) shown in Figure 6. The data sources are cited in Figure 6.

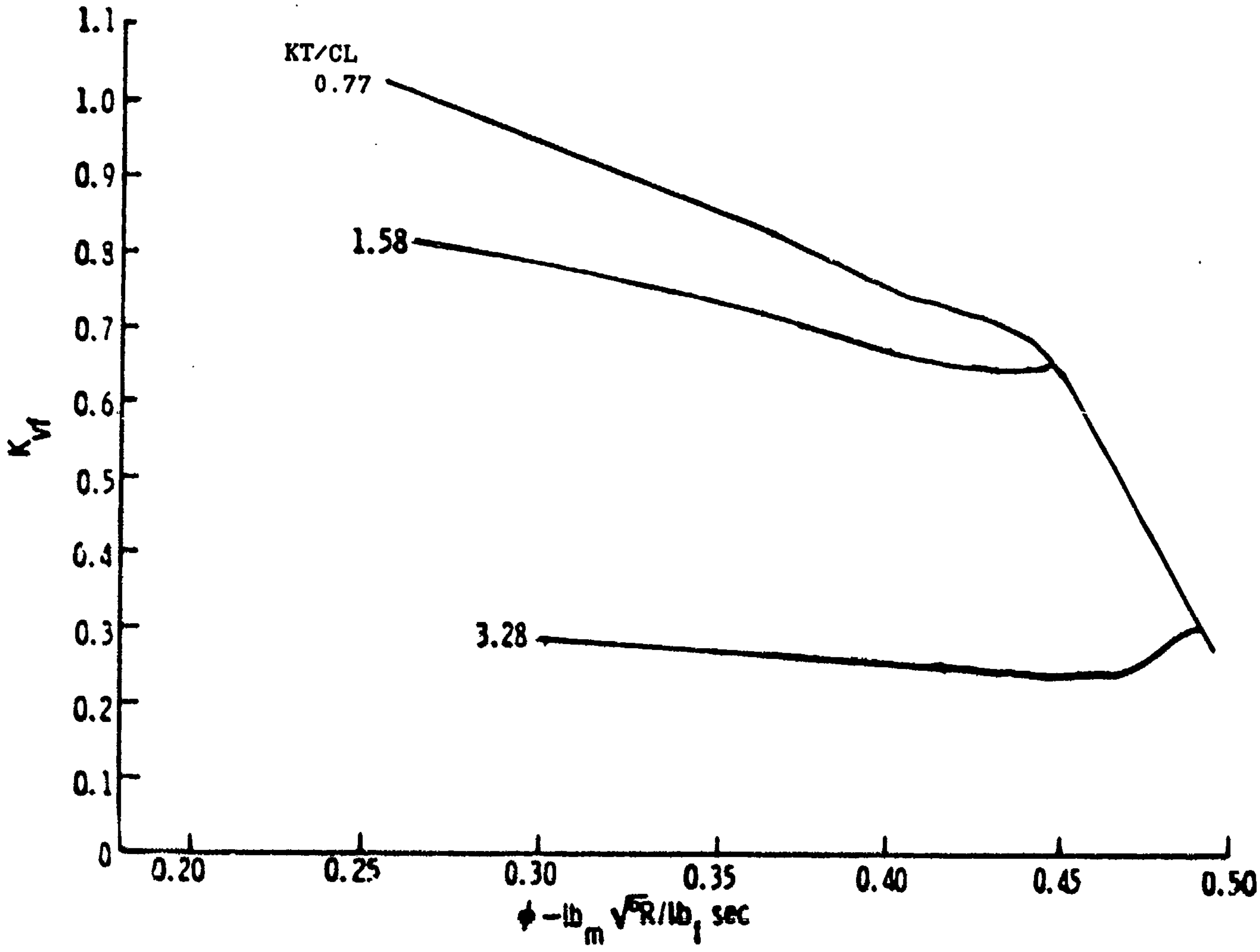

Figure 5. Venturi-friction coefficent from Kearton and Keh data.

K_e = 1.0

K_{vf} = $f(\phi, KT/CL)$

Figure 5: $0.77 \leq KT/CL \leq 3.3$, but good for $0.0 \leq KT/CL \leq 3.3$

[Derived from Kearton and Keh data for $K_c = 0.70$ (KR very small)]

$$K_{c\ @\ 90°} = 0.7\left\{1. - \text{EXP}\left[C_1 - C_2\ \phi^2\left(\frac{CL}{KR}\right)^{0.25} + C_3\left(\frac{KR}{CL}\right)\right]\right\}$$

where

KR - in.	from	Data Source
0.0		KEARTON & KEH (31)
0.00167		Allison
0.005		KOMOTORI & MIYAKE (37)
0.005		HARRISON (23)
0.010		CAUNCE & EVERITT (13)

K_c = $K_{c\ @\ 90°}$ for $K\theta = 90°$

K_c = $K_{c\ @\ 90°} \times [1. - C_4\ (K\theta - 90°)]$ for $K\theta > 90°$ [from IDEL'CHIK (27)]

K_c = $K_{c\ @\ 90°} + C_5\ [1. - \text{SIN}\ (K\theta)]$ for $30° \leq K\theta \leq 90°$ [from Allison plus MEYER AND LOWRIE data (43)]

NOTE: $K\theta$ is actual front surface angle relative to the flow direction so that $K\theta = 90° + K\beta/2$ when the specified knife angle is vertical or beyond, $K\theta \geq 90°$.

C_n = constant, the value of which is given in the User's Manual program listing for the Design Model (68).

Figure 6. Loss coefficient correlations for a single-knife seal.

Contraction losses are affected by the slant angle ($K\theta$) of the knife. The effectiveness of a knife increases, i.e., the K_c becomes larger, as the knife is slanted into the flow ($K\theta < 90°$). Likewise the knife leakage increases, i.e., the K_c becomes smaller, as the knife is slanted backward with the flow ($K\theta > 90°$). The contraction loss coefficient for reentrant knives in the range $30° \leq K\theta \leq 90°$ was correlated from the test data of Meyer and Lowrie (43) and Allison. The effect of backward slanted knives was obtained from a correlation by Idel'chick (27). The modifications to the K_c correlation for vertical knives which correct for a knife taper angle ($K\beta$) are noted in Figure 6.

The physical relevance of the correlation equations can be evaluated best by comparing the predicted performance of single-knife seals with their measured performance. An example of the good agreement obtained is shown in Figure 7. The single-knife seal performance algorithm was the basis for the model development for multiknife straight and stepped seals.

4.3 STRAIGHT SEAL MODEL

The single-knife seal model was extended to multiknife seals by linking the triplet losses for each knife in the series. The overall pressure loss is the summation of the individual total pressure losses at each knife. The losses are calculated sequentially starting with the known inlet pressure because the loss coefficients and Mach number are functions of the local parameter ϕ. For a straight seal, there is a carry-over of the velocity head from an upstream knife. This carry-over through the interknife cavity affects the K_{vf} and K_e of the upstream knife and the K_c and K_{vf} of the downstream knife. Thus, all the loss coefficients of a multiknife straight seal are influenced by the adjacent knives except the K_c of the first knife and the K_e of the last knife. The modeling approach followed for multiknife seals was to determine the three loss coefficients for a given knife location from the single knife correlations of Figure 11 and then to correct them for the effects of adjacent knives. The corrections are based on the expansion angle of the carry-over jet discharging from the clearance gap over a knife. This approach

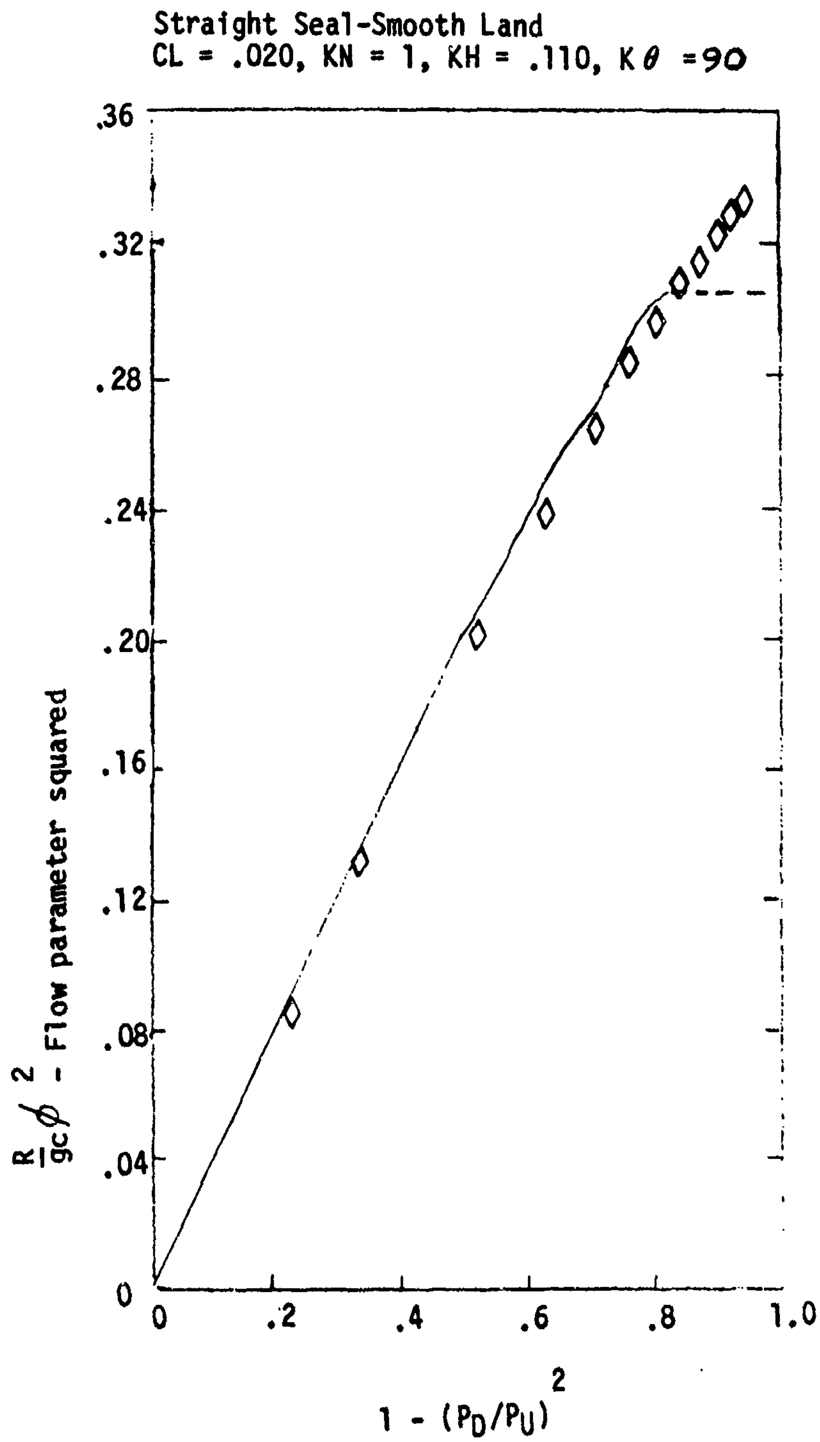

Figure 7. Model results compared to Allison data for a single-knife seal.

has been proposed by Abramovich (1) and utilized by Komotori and Miyake (37) in their KTK model. The carry-over expansion angle, α, is defined by the straight seal schematic in Figure 4. The flow in the jet expands until it impinges on the upstream face of the next knife. The maximum downstream flow height is (CL + δ) so that the expansion area ratio is (CL + δ)/CL. The upper limit of the expansion area ratio, 1 + KH/CL, is encountered with short knives, with large knife pitch, and after the last knife in the seal. This jet expansion ratio not only represents the amount the flow expands from the upstream knife but also the contraction into the downstream knife gap. The equations for δ in terms of α and the other geometric parameters in Figure 4 are:

for vertical knives ($K\theta = 90°$)

$$\delta = (KP-KT)/[\mathrm{Tan}\ K\beta + (1/\mathrm{Tan}\ \alpha)] \qquad 4.7$$

for slanted knives ($\alpha < K\theta < 90°$)

$$\delta = (KP-KT)/(\mathrm{Cot}\ \alpha - \mathrm{Cot}\ K\theta) \qquad 4.8$$

To incorporate the effects of α on the three loss coefficients, relationships proposed by Dodge (16) were utilized as follows from Figure 3:

<u>SUDDEN CONTRACTION</u>

$$K_c = K_c' \left[1 - \frac{A_t}{A_1}\right] \qquad 4.9$$

<u>VENTURI WITH FRICTION</u>

$$K_{vf} = K_{vf}' \left[1 - \frac{A_t}{A_1}\right]^{1/2} \left[1 - \frac{A_t}{A_2}\right] \qquad 4.10$$

<u>SUDDEN EXPANSION</u>

$$K_e = K_e' \left[1 - \frac{A_t}{A_2}\right]^2 \qquad 4.11$$

The ratios A_t/A_1 and A_t/A_2 are simply the ratio $CL/(CL + \delta)$ relative to the upstream and downstream sides of a given knife, respectively.

In general, the expansion angle will vary from knife to knife as the pressure ratio varies. This was observed in the flow visualization test results. The expansion angle variation was not modeled, however, because of the lack of complete seal performance with interknife pressure data. The Design Model could be developed to include α variation through the seal based on results from Analysis Model calculations and/or test data.

Equations 4.7 through 4.11 were formulated in the Design Model with α as an independent variable. Straight seal performance for geometries in the data base was calculated for a range of α values. Comparing model results with the test performance data yielded the average α for each seal configuration. Figure 8 shows a typical comparison of test data with the model results for assumed values of α. From this plot, an average α value of 3 deg was detemined for the tested straight seal configuration. Table 7 summarizes the range of α values obtained from the various data sources. The α range obtained for the data of Komotori and Miyake (37) compares well with the value of 6 deg reported in a discussion of their paper.

A linear regression analysis was performed on the α results. The jet expansion modeling equation obtained is given in Figure 9.

Table 7.
Jet expansion angle (α) for straight seals as determined by correlation.

o	Caunce and Everett, 6 knife	= 6 - 8 deg
o	Komotori 2, 4, 8, and 10 knife	= 4 - 6 deg
o	Allison 4 knife	= 2 - 4 deg
o	Allison 8 knife	= 4 - 5 deg
o	Allison 4, 5 knife slanted	= 2 - 4 deg

FOUR SLANT KNIFE STRAIGHT SEAL - SMOOTH LAND
CL = .010, KN = 4, KP = .110, Kθ = 60°, DIR = 81

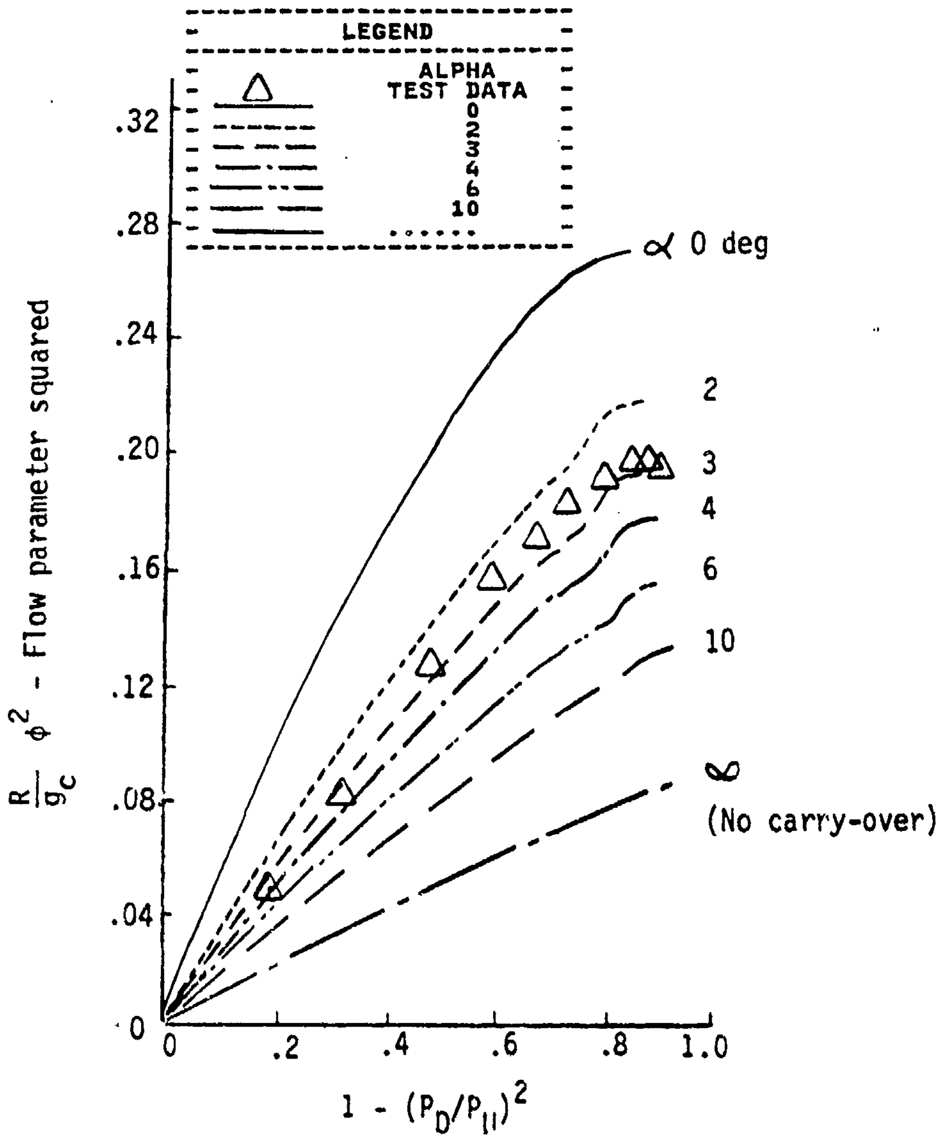

Figure 8. Determination of α for straight seals.

JET EXPANSION ANGLE

$$\alpha = C_6\sqrt{\frac{KP-KT}{KH}}$$

for

$$0.54 \leq \frac{(KP-KT)}{KH} \leq 4.0$$

Average deviation = 25%

C_6 = constant. The value of this constant is given in the User's Manual program listing for the Design Model (68).

WALL ROUGHNESS

$$K_{vf} = K_{vf\ smooth}\ (\text{Correction for upstream and downstream knives}) + K_{f\ rough}$$

where

$$K_{f\ rough} = f\ (\epsilon/H,\ Re,\ KP)$$

$$A_t = A_{t\ smooth}\left(\frac{CL + \epsilon}{CL}\right)$$

Figure 9. Straight seal correlations in the Design Model.

The effect of land roughness was included in the model by adding a frictional head loss term ($K_{f\ rough}$) to the venturi loss coefficient ($K_{vf\ smooth}$). A wall friction loss coefficient ($K_{f\ smooth}$) for a smooth land is the baseline for K_{vf}. The flow area in each knife throat was increased to account for the increase in clearance due to the land roughness. An explicit equation for the Fanning friction factor was obtained from regression analysis:

$$4f = \frac{6.02 - 138.41 \frac{(\epsilon-30)\ 10^{-6}}{H}}{\left\{0.825 \log_{10}\left[10/Re + .2 \frac{(\epsilon - 30)\ 10^{-6}}{H}\right]\right\}^2} \qquad 4.12$$

where $4f \geq 0$.

This equation is similar in form to the implicit equation for transition flow in rough conduits that was proposed by C.F. Colebrook. The frictional head loss coefficient was determined as

$$K_{f\ rough} = (4f_{rough} - 4f_{smooth})\ \ell/H \qquad 4.13$$

where $H = 2\ CL$

The knife-to-knife flow analysis was maintained by utilizing a rough wall length equal to the knife pitch of the downstream knife. Consequently, the rough wall length for the last knife is equal to the knife tip thickness. Figure 9 outlines the modeling for wall roughness. Figure 10 shows a comparison of model results to test data for a rough straight seal land and a corresponding smooth land. The model accurately accounts for the effect of roughness for the seal geometry evaluated.

Comparisons of Design Model predictions with the straight seal test data show that, based on overall average, the model is accurate within $\pm$ 5%. Figure 11 is a typical example of these comparisons.

Table 8 summarizes the model deviation from the test data for the single-knife and multiknife straight seals in the data base.

Table 8.
Design Model error results for straight seals.

Type	Source	Number of Configurations	Avg. Error* (%)
Single knife	Kearton & Keh	3	1.4
	Caunce & Everitt	6	1.2
	Komotori & Miyake	1	1.8
	Allison (including slanted knives)	8	3.5
Multiple knife	Caunce & Everitt	4	3.5
	Komotori & Miyake	12	4.3
	Harrison	13	5.9
	Allison (including slanted knives and roughened lands)	26	4.6
	All	73	4.2

*Average error is the arithmetic mean of the average deviations between model and test data.

CL = .020, KN = 4, KΘ = 90, KP = .110, KH = .110,
KT = .010, DIR. = BI

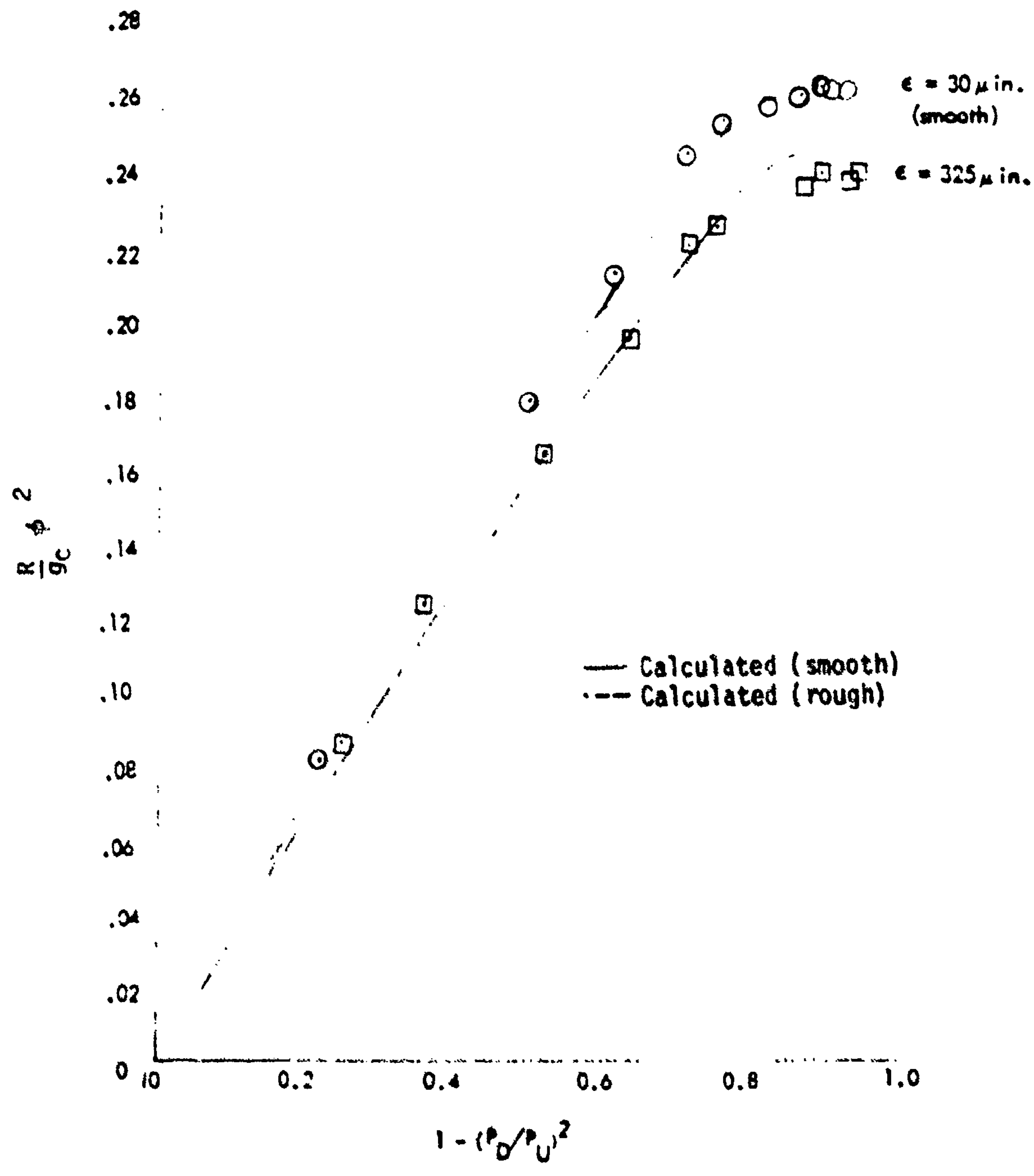

Figure 10. Model compared to Allison 2-D rig test data for straight seals with smooth or rough lands.

FIVE SLANT KNIFE STRAIGHT SEAL - SMOOTH LAND

CL = .010, KN = 5, KP = .110, KH = .110, K θ = 60, DIR = 81

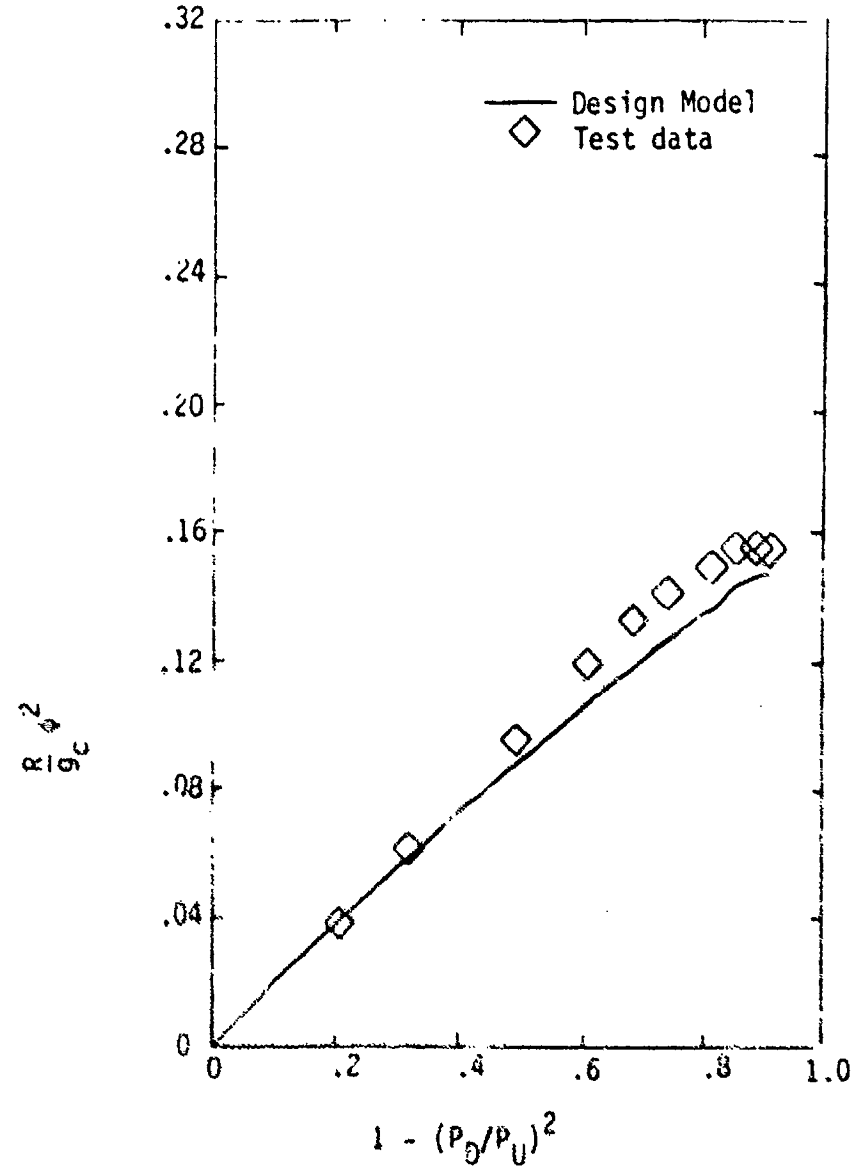

Figure 11. Model compared to Allison 3-D rig test data for a slanted five-knife straight seal with a smooth land.

4.4 STEPPED SEAL MODEL

Stepped seals are designed to minimize the dynamic pressure recovery from one knife to the next by disrupting the velocity carry-over. Accordingly, the straight seal model approach which correlated the jet expansion angle in terms of cavity dimensions has limited physical applicability to stepped seals. The test data show that stepped seals flow both more and less than comparable straight seals depending primarily on the operating clearance. Consequently, a more comprehensive model is required to account for the influence of the additional geometric parameters of step height (SH) and distance-to-contact (DTC) which affect the performance of STLD and LTSD stepped seals differently.

Physically, the flow between knives in a stepped seal does carry-over some of the velocity head to the next knife. But while the intervening flow path dissipates a large part of the velocity head, it also affects how the flow enters the next knife and, thereby, influences the loss coefficients of that knife. The complex flow patterns involved would make correlations for corrections to the individual loss coefficients difficult to determine accurately. Consequently, a different approach was taken to include all of the diverse flow distortion and loss mechanisms into a single area correction factor (XMUL) for a knife throat downstream of a step. This factor is a multiplier on the flow area and can be less than or greater than unity. It accounts for carry-over, additional pressure loss in the flow turning between the knife face and step, which is important for small distances to contact (DTC), and flow distortion into the next knife throat.

The basic model for stepped seals assumes that the flow behaves as if it were passing through a series of single-knife seals. Correlations for XMUL were obtained through a procedure similar to that followed to evaluate α for straight seals. For a range of XMUL values performance predictions were calculated from the Design Model for the stepped seal configurations in the data base. A comparison of these results with the test data yielded the required XMUL value for each configuration. Figure 12 shows a typical comparison plot. The area multiplier (XMUL) was found to vary from 0.55 to 1.32. A correlating equation for XMUL in terms of the influential geometric parameters

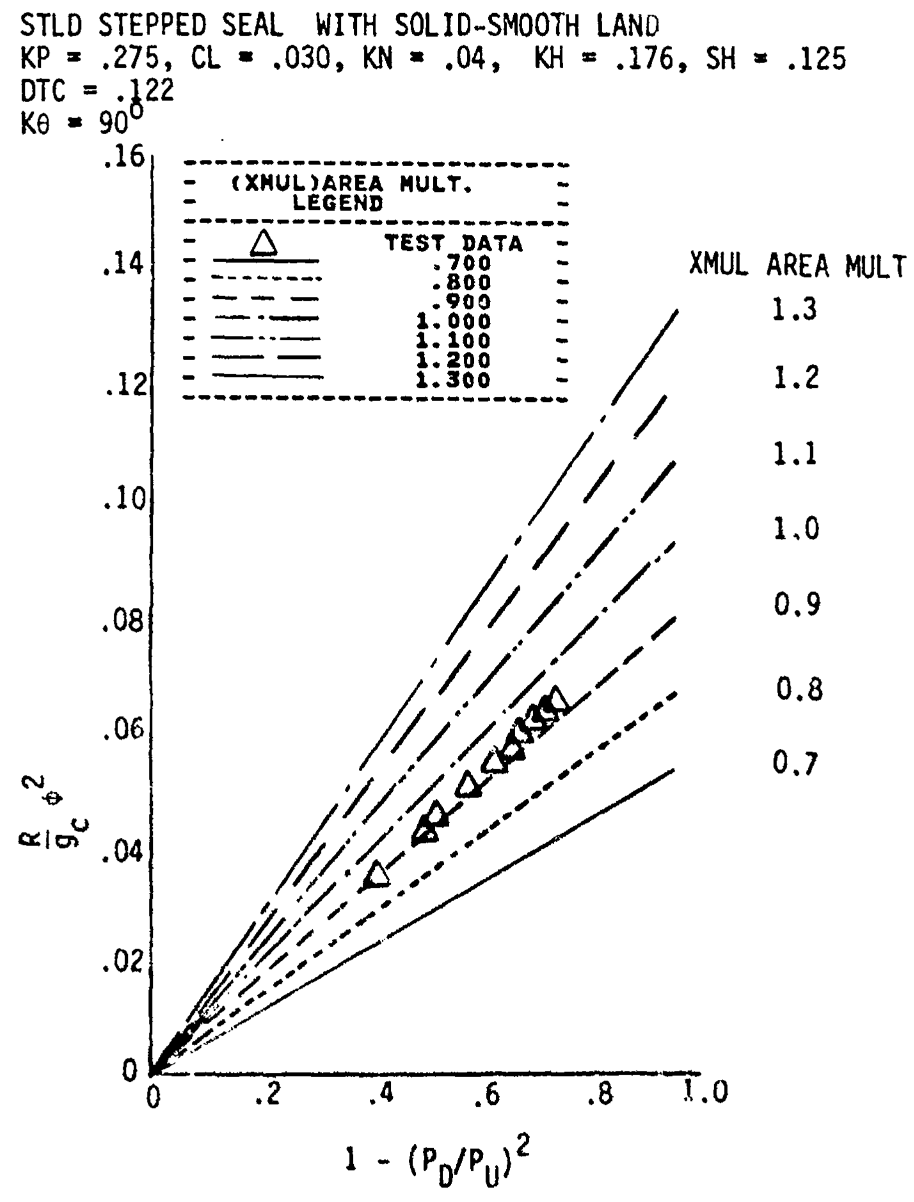

Figure 12. Determination of the area multiplier for a stepped seal.

was derived using a multiple linear regression analysis. Stepped seals with STLD flow direction, backward facing stator steps, were analyzed first because of the larger data base (62 configurations). A correlation for the LTSD flow direction was obtained from comparisons of the STLD equation to the LTSD test data (15 configurations). A correction equation based on the comparable STLD stepped seal was derived. This approach provided the best extrapolation of the narrower parameter ranges for the LTSD stepped seal data. Figure 13 gives the STLD and LTSD correlations for XMUL and their respective parameter ranges.

Roughened land surface effects for stepped seals were handled in the model with a procedure similar to that developed for straight seals, i.e., adding a friction head loss term ($K_{f\ rough}$) to the K_{vf} for a smooth wall and increasing the throat area by the amount of the roughness. The effective length of the rough wall was taken equal to the knife tip thickness because the steps induce significant flow separation in the interknife cavities. This wall friction model produces good agreement with the test data.

Figures 14 and 15 show typical comparisons of model results with test data in the data base. The Design Model deviations from the test data are summarized in Table 9 for all of the stepped seal data in the data base. The disagreements between test data and Design Model predictions are within $\pm 5\%$.

STEPPED SEAL AREA MULTIPLIER, XMUL

STLD Flow Direction

$$XMUL = C_7\ (DTC/CL)\ (KT/CL)^{C_8}\ (DTC/(KP-KT))^{C_9}\ (KH/CL)^{C_{10}} \ldots$$

$$\ldots ((KP-KT)/KH)^{C_{11}}\ (SH/CL)^{C_{12}} \Big/ \sqrt{(DTC/CL)^2 + C_{13}}$$

$0.85 \leq DTC/CL \leq 40$, $0.21 \leq KT/CL \leq 2.6$, $0.09 \leq DTC/(KP-KT) \leq 1.0$,

$5.1 \leq KH/CL \leq 19.4$, $1.16 \leq (KP-KT)/KH \leq 1.76$, $2.0 \leq SH/CL \leq 29.4$

LTSD Flow Direction

$$XMUL = XMUL_{STLD}\quad C_{14}\ (KH/CL)^{C_{15}}$$

$4.0 \leq DTC/CL \leq 19.4$, $0.50 \leq KT/CL \leq 1.5$, $0.35 \leq DTC/(KP-KT) \leq 0.50$

$5.1 \leq KH/CL \leq 28$, $1.02 \leq (KP-KT)/KH \leq 1.9$, $4.0 \leq SH/CL \leq 12.5$

Note: The limits on the seal parameters result from the range of the seal geometries used in developing the correlation equations.

WALL ROUGHNESS

$$K_{vf} = K'_{vf} + K_{f\ rough}$$

$$K_{f\ rough} = f(\epsilon/H,\ Re,\ KT)$$

$$A_t = A_{t\ smooth} \left(\frac{CL + \epsilon}{CL}\right)$$

Figure 13. Stepped seal correlations in the Design Model.

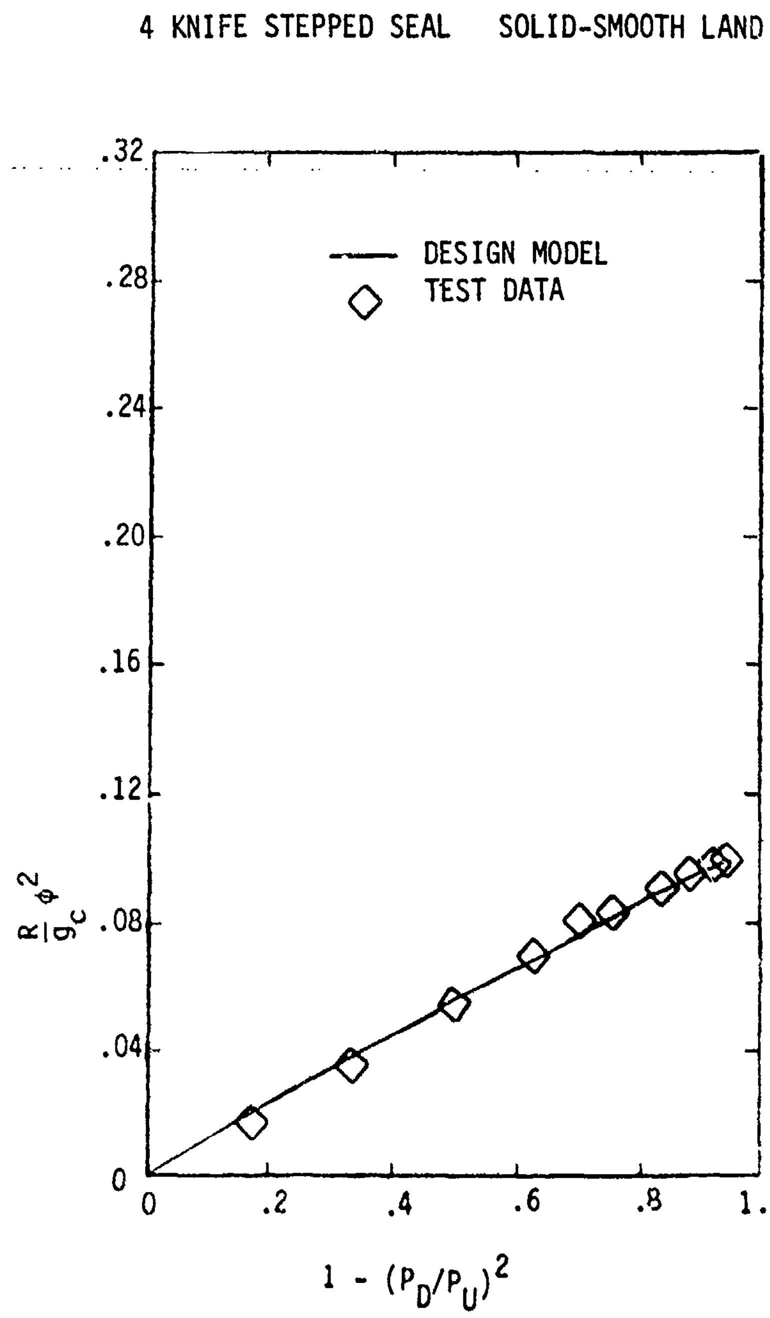

Figure 14. Design Model compared to Allison test data for a stepped seal with a solid-smooth seal.

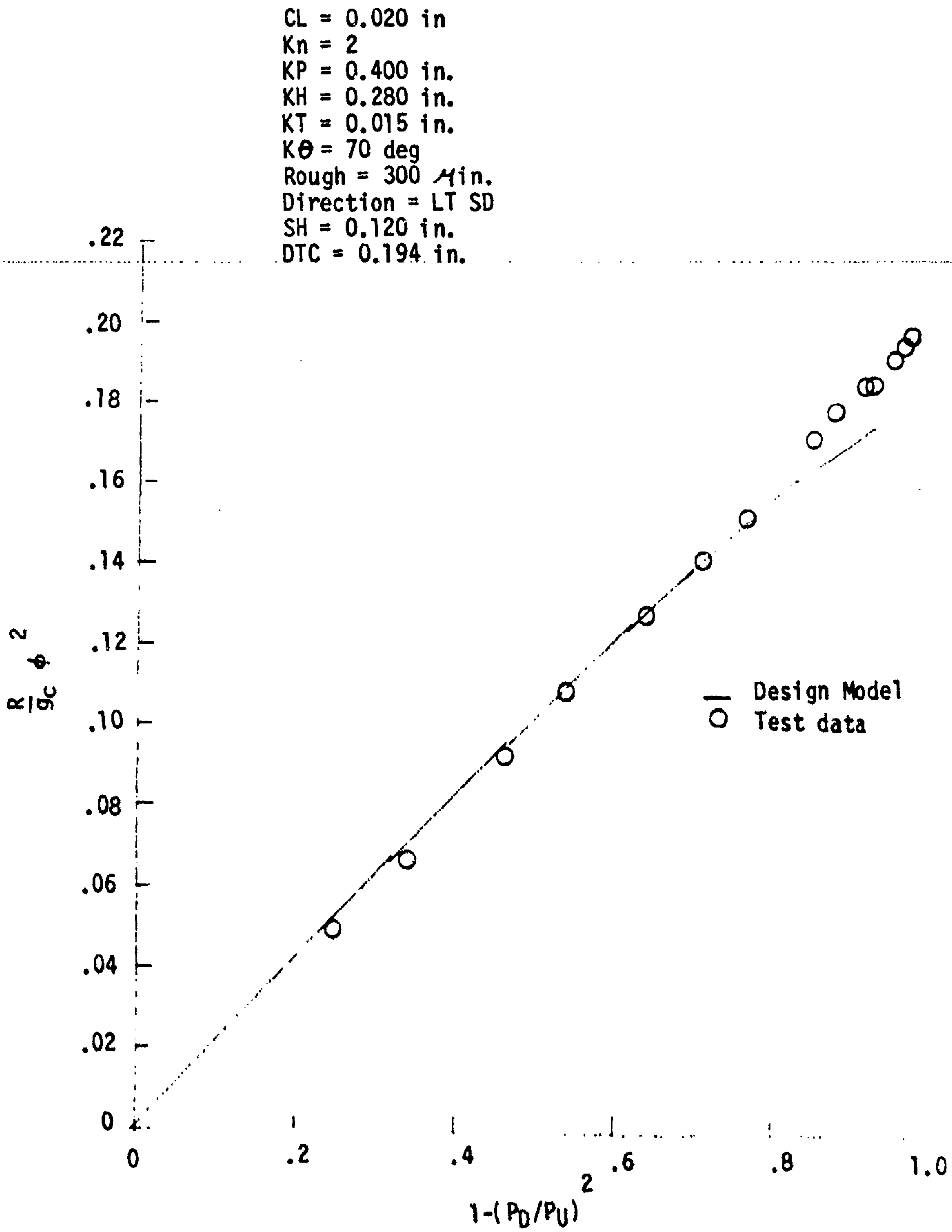

Figure 15. Design Model compared to Allison test data for a stepped seal with a rough land.

Table 9.
Design Model error results for stepped seals.

Type	Source	Number of Configurations	Avg Error* (%)
Multiple knife	Caunce & Everitt (STLD only)	44	2.9
	Harrison (STLD only)	8	5.3
	DDA		
	STLD data	9	4.0
	LTSD data (includes roughened land)	24	4.8
	Both	33	4.6
	All	85	3.8

*Average error is the arithmetic mean of the average deviations between model and test data.

4.5 DESIGN MODEL COMPUTER PROGRAM

The Design Model for calculating the flow through labyrinth seals has been coded in Fortran IV language for rapid and comprehensive computations. The one-dimensional compressible flow equations satisfactorily represent the flow in the knife throats when they are coupled with empirical relationships for the loss coefficients. This semi-empirical analysis also gives the pressure distribution through the seal. The model accurately predicts straight and stepped seal leakage within ±5% for a wide range of seal parameters encountered in gas turbine engines. Since the model considers one knife at a time, non-constant geometry seals, e.g., different clearance at each knife tip, can be considered. Nonconstant seal geometry can accommodate mixed straight and stepped configurations in a single seal.

Features available in the Design Model code include:

- abbreviated input where possible
- override available for many of the loss coefficient parameters
- function loss can be specified instead of or in addition to the three loss coefficients
- nonconstant geometry straight and stepped seals, or a mixed combination of the two, can be considered
- calculations for two-dimensional (rectangular) seals are possible to simulate some static seal rigs.
- calculation options are available:
  pressure distribution for a given flow rate.
  pressure distribution and flow rate for a given overall pressure ratio.
  flow characteristic curve (ϕ versus P_R).

A comprehensive description of the structure, capabilities, and use of this computer code is presented in Reference (68).

A Design Model verification test was made with previously untested stepped seal hardware. This seal configuration was not part of the data base used to derive the Design Model. The vertical knife stepped seal was tested in the STLD configuration statically and dynamically at 246 and 492 ft/sec average knife tip speeds. The measured performance and the performance predicted by the design model are plotted in Figure 16. Table 10 compares the design model performance predictions with the test data. The correlation between measured and predicted seal performance was within one percent throughout the pressure ratio range tested. Although this was a single point check, the predictive capability of the Design Model within the limits specified for the labyrinth seal parameters is expected to be within ±5% of the true value for conventional seal configurations at clearances greater than 0.005 in.

Table 10.
Comparison of the verification test results with the Design Model performance prediction.

P_U/P_D	Φ - $\frac{lb_m\ °R^{1/2}}{lb_f\ sec}$ Design Model	Verification test static condition (V.T.)	$\frac{\Delta\Phi}{\Phi_{V.T.}}$ - %
1.0	0	0	
1.25	0.1508	.152	-0.8
1.50	0.1857	.187	-0.7
2.00	0.2142	.216	-0.8
3.00	0.2318	.234	-0.9
4.50	0.2379	(.237)*	(+0.4)
Average			-0.8

*Extrapolated from elliptical coordinate plot of the measured data. Not included in overall average.

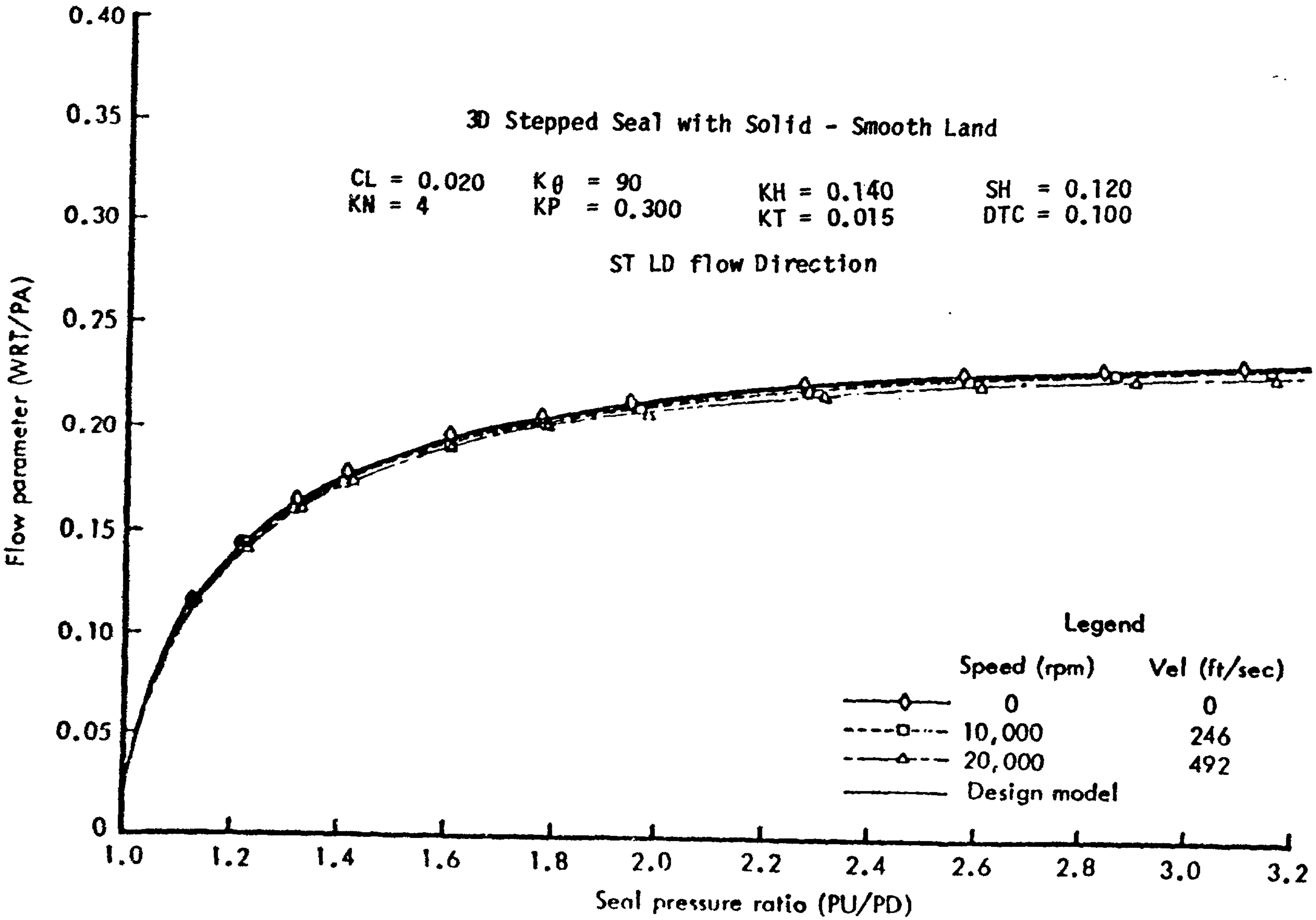

Figure 16. Design Model performance--predicted and measured.

5.0 LABYRINTH SEAL DESIGN OPTIMIZATION

The Design Model is a performance analysis tool for a specified labyrinth seal geometry. The seal designer often needs to solve the inverse problem: configure a seal to minimize the leakage for a particular application. The seal design is generally constrained by installation and fabrication limits. Consequently, the haphazard selection of candidate seals from among the myriad possible designs on the sole basis of experience criteria will seldom result in a "best" choice. However, mathematical optimization theory provides a reliable and efficient iterative procedure for determining the best seal design.

5.1 OPTIMIZATION ALGORITHM

The optimization of a seal geometry from the performance predicted by the Design Model requires the maximization of nonlinear functions of the independent variables, which are subject to nonlinear equality or inequality constraints. The nonlinear constrained optimization is transformed to an unconstrained problem through the use of a penalty function. Then the variable metric method of Fletcher-Power-Davidon is used to solve the problem. This approach applies to continuous variables and is reliable even for erratic functions that are frequently encountered in design problems.

Discrete variables, e.g., the type of seal, the number of knives, and the flow direction, are also encountered in the optimization problem. The algorithm performs the continuous variable optimization for each set of discrete variable values. Then the individual optimum designs are compared to determine the overall optimum seal design.

Constraints have been included in the algorithm to ensure that the optimized seal configuration satisfies the design requirements. Constraints on the discrete variables simply limit the matrix of values considered in the trial and comparison procedure. Constraints on the continuous variables are imposed by adding inequality penalty functions to the functions being optimized. A penalty function equals zero if the design meets a given contraint. It is greater than zero if the constraint is violated, and the penalty varies parabolically with the magnitude of the violation. Each continuous variable constraint has one penalty function associated with it.

A driver routine has been programmed for the Design Model code which calculates the independent parameter values to be evaluated in the search for an optimum configuration. This driver automates the procedure of: (1) determining the overall design constraints, (2) selecting the allowable range of each parameter to meet design and model constraints, (3) using the Design Model to calculate the leakage flow rate for a matrix of possible seal configurations, and (4) optimizing the seal design from the performance matrix, i.e., finding the seal geometry with the lowest leakage.

5.2 OPTIMIZATION CAPABILITIES

Three types of parameters are involved in the seal optimization process: (1) input parameters which are held at specified constant values during the optimization, (2) optimized parameters which will define the unique best seal configuration, and (3) constraining correlation parameters which limit the parametric search to the Design Model envelope. The optimization of a seal design can consider a matrix of these parameters listed in Table 11. Input parameters have constant values imposed by the operating environment of the sealing application or by physical limitations of the design or fabrication processes. The parameters defining a maximum seal geometry envelope, i.e., L_{max} and H_{max}, are optional and should be stipulated only if the space allocated to the seal is limited. The optimized parameters are either continuous or discrete functions. Each discrete parameter defines an optimization matrix which is solved by the variable metric method. The optimum solutions for each discrete parameter are compared to obtain the best seal configuration. The constraining correlation parameters limit the selection of the best seal design so that the parametric correlations in the Design Model are not extrapolated beyond their reliable range. Alternative constraints can be superposed on the optimization by the input of minimum and maximum values for the continuous and discrete optimized parameters. These additional constraints are arbitrary and optional, similar to the use of the overall seal length and height specifications. If the program limits on an optimized parameter are not overridden by input data, the constraining limits are set by default to the code values.

Table 11.
Design Model optimization parameters.

Input Parameters	Optimized Parameters
Straight and Stepped Seals	**Continuous Variables**
Clearance (CL)	Knife height (KH)
Temperature (T)	Knife pitch (KP)
Inlet total pressure (P_U)	Knife tip thickness (KT)
Pressure ratio (P_R)	Knife angle (Kθ)
Knife radius (KR)	Roughness (ϵ)
Knife taper angle (Kβ)	Step height (SH)**
Maximum axial length (L_{max})*	
Stepped Seals Only	**Discrete Variables**
Maximum seal height (H_{max})*	Seal type (straight, stepped)
Distance to contact (DTC)	Number of knives (KN)
Maximum or minimum diameter (D_{max}, D_{min})	Flow direction (LTSO, STLO)**
Minimum knife pitch (KP_{min}) (= 2X maximum allowable axial travel)	

*Optional
**Stepped seals only

Constraining Correlation Parameters

Straight Seals	Stepped Seals
KT/CL	KT/CL
Kθ	Kθ
(KP-KT)/KH	(KP-KT)/KH
(ϵ - 30)/CL	DTC/CL
	SH/CL
	KH/CL
	(ϵ - 30)/CL

The optimization code capabilities can be summarized as follows:

- o Constant geometry straight and stepped seals can be considered. However, variable parameters from knife-to-knife or mixed straight and stepped seal geometries cannot be optimized.

- o An optimum configuration may be determined for both seal types and for both flow directions through the stepped seals. Any subset of these may be considered.

- o Each independent parameter has a default range which may be overridden. Even the correlation parameter ranges may be overridden if desired.

- o An independent parameter may be held constant (by inputting both its minimum and maximum values equal to the one desired).

- o Before optimization is attempted, the parameter values and ranges are checked to be sure a solution is possible, e.g., a solution is impossible if L_{max} is less than the minimum KP divided by the maximum KN. If a solution does not exist, information is printed describing the problem, and the execution of the data set is halted.

- o Intermediate output information is given for each combination of discrete variables employed. This output information includes algorithm parameter values, derivatives of the optimized function with respect to each continuous variable, and comparisons of the continuous variable values with the allowable ranges.

- o Final output information includes sensitivity results for each discrete variable step and summary data for the optimum seal configuration designated.

The output information not only defines the optimum seal configuration but indicates the effect, if any, of imposing each constraint. Also, the improvement in decreased leakage of the optimum configuration compared to the other possible configurations is given. This information can be used to assess the penalty caused by each limiting constraint and the penalty for choosing an alternate design.

A detailed description of the optimization algorithm and its use with the Design Model code can be found in the User's Manual (68). A sample input file and the resulting optimum seal configuration output are included.

6.0 LABYRINTH SEAL EXPERIMENTAL INVESTIGATION

The labyrinth seal rig tests were designed to extend the ranges of geometric parameters in the data base for the design model development, to provide verification of the capabilities of both the Design Model and the Analytical Model, and to substantiate the physical reality of the flow-field structure calculated by the Navier-Stokes analysis model. The bulk of this seal performance testing was done in the two-dimensional (2-D) static rig. This rig was also utilized as the test section for schlieren flow visualization and flow field velocity measurements in large-scale seal models. Supporting performance tests were made independently with intracavity pressure and temperature instrumentation. A program to characterize the leakage performance of typical straignt seals and stepped seals with open-cell honeycomb lands was run statically and dynamically in the three-dimensional (3-D) test rig. The effects of knife rotation on full-scale straight seals with smooth and rough lands were investigated using intracavity pressure instrumentation. Verification tests were run on the 3-D dynamic rig with a seal configuration which had not been previously tested.

6.1 TEST RIGS AND PROCEDURES

Two complementary test rigs were used to acquire the variety of data required to support the development of the analytical models. A cost effective two-dimensional (2-D) static rig was employed to obtain the seal performance data for the full-scale models of straight and stepped seals under the influence of geometric and land surface roughness variations. This 2-D rig was also used to study the internal details of the labyrinth seal flow through large-scale models which were also suitable for flow field velocity measurements with hot-wire anemometers and for flow visualization with a schlieren technique developed specifically for the purpose. A three-dimensional (3-D) dynamic rig was used to investigate the performance perturbations imposed by rotating knives next to several different land materials with annular clearance gaps. The following sections describe the test equipment and instrumentation utilized to obtain these data.

6.1.1 2-D Static Rig

The terminology, 2-D (two-dimensional) static test rig, is based on the seal models which are installed in the rectangular test section. These models do not simulate the effects of seal curvature or rotation and involve small end-wall effects. However, the high aspect ratio test section, 6.28 in. wide, minimizes these end effects.

Building block, adjustable seal hardware is used to obtain versatility and multiple use of components. Individually adjustable knife and land sections can produce continuous changes in the primary geometric variables of straight and stepped seals in a cost effective manner. The features incorporated in the rig design, Figure 17, allow one set of knife hardware to cover the conventional range of variation in:

- o knife clearance
- o knife pitch
- o knife height
- o number of knives
- o step height
- o distance-to-contact (axial clearance)

The maximum test envelope will accommodate a seal length of 2.0 in. This test section will allow a considerable number of straight seal knives (depending on pitch) and stepped seal knives to be tested at full-scale over a complete range of clearance encountered in small and large high-temperature aircraft engines.

Figure 18 shows a close-up view of the 2-D rig test section with a four-knife stepped seal installed. Each knife and each land are an individual horizontal piece and can be adjusted in an axial direction relative to adjacent pieces to make arbitrary changes in the pitch. Step height can be varied by inserting shims (not shown) between adjacent knife and land sections. The knife pitch and axial seal clearance (DTC) can be easily changed with the adjustment

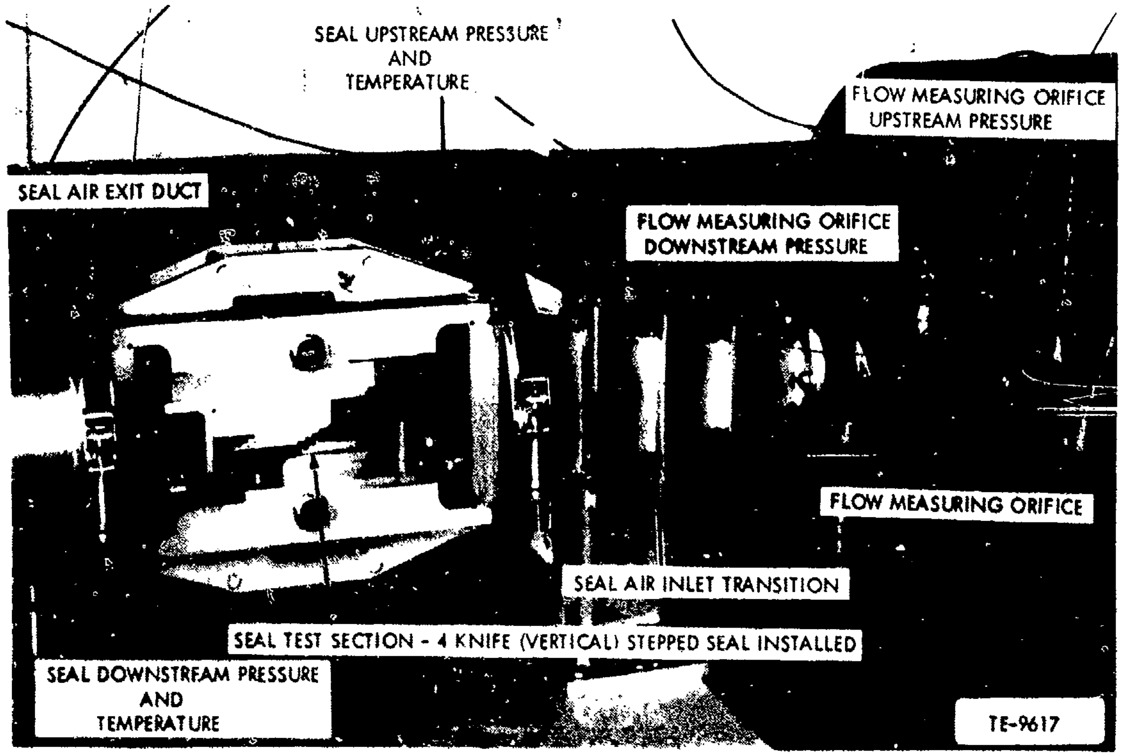

Figure 17. Two-dimensional (2-D) labyrinth seal air test rig installation.

screws as shown in Figure 18. Vertical clearances between the corresponding lands and knives can be varied by clearance shims as noted. Changes in knife height are accomplished by filling the knife cavities with low temperature pattern wax. The number of knives are easily variable by removing or adding corresponding knife and land sections. For vertical knife seals, the flow direction through the seal can be changed by reversing the knife and land foundations. Changes in knife angle and land contour do require different hardware.

Figure 19 shows a close-up view of a four-knife straight seal installed in the 2-D test section. The straight-seal assembly is similar to, but simpler than, that for the stepped seal since one land section is required. Spacers between knives, with specific height and thickness dimensions, are used to adjust knife pitch and height in the straight seal.

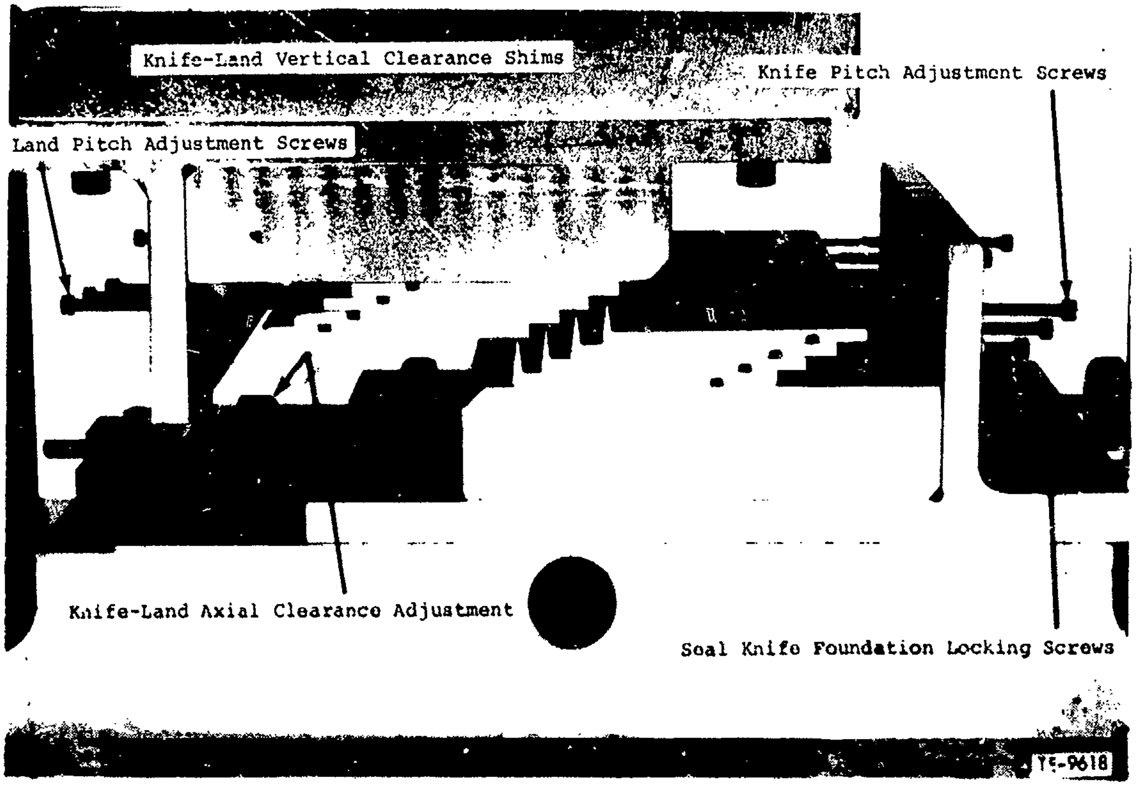

Figure 18. Two-dimensional (2-D) labyrinth seal rig with stepped seal installed.

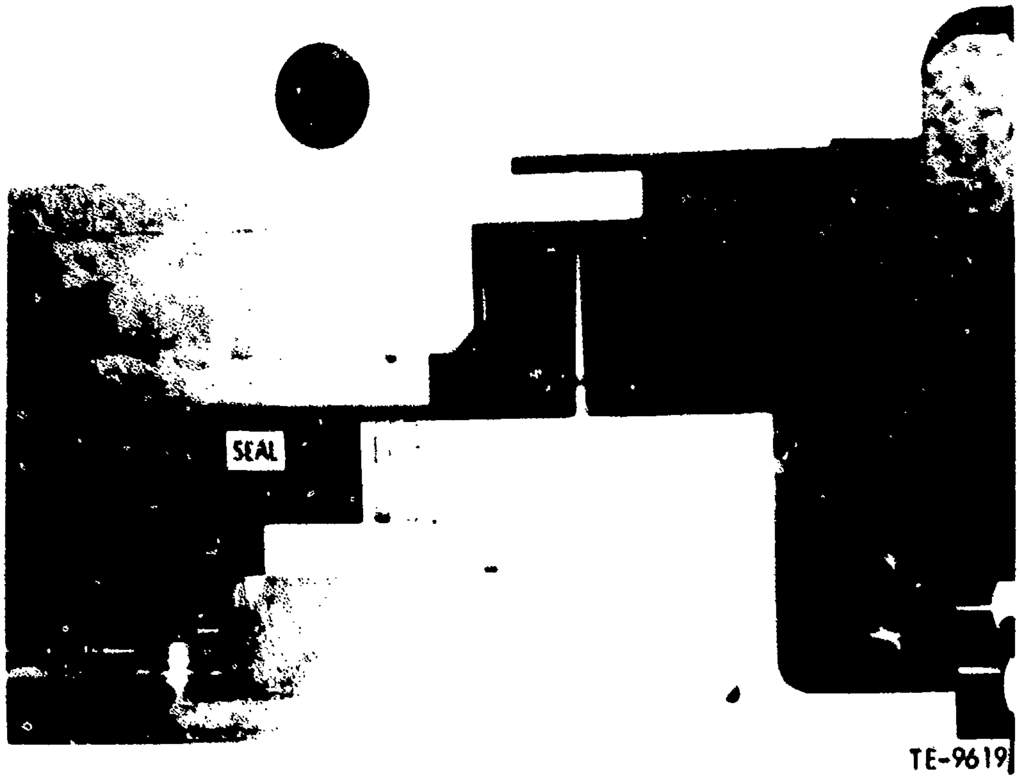

Figure 19. Two-dimensional (2-D) labyrinth seal rig with straight seal installed.

The 2-D rig installation permits aerodynamic evaluation of seal performance to a seal inlet pressure of eight atmospheres at room ambient temperature. The test condition range and the local Mach numbers encountered in the seal flow limit pressure and temperature variations in air to compressibility factors, $Z = P_s/Rt$, near unity. The desiccated air supply prevents the possibility of variation in the test fluid due to composition changes and removes any chance of condensation shocks. The rate of change of thermal characteristics, c_p and γ, for air is small in the ambient temperature range. Therefore, the 2-D rig test environment enhances the accuracy and generality of the data reduction procedures. The primary modeling variable which is not controlled is Reynolds number, which varies primarily with seal model scale.

The rig normally discharges to the atmosphere outside the test cell through a 5.76 in. inner diameter (I.D.) pipe which creates less than 0.2 psi pressure loss.

The flat plane walls forming the rectangular test section of the 2-D rig experience small structural deflections which can result in clearance changes under high air pressure loading. A micrometer dial gauge (see Figure 20) with 0.00002 in. readability is mounted on the top plate to monitor the relative movement of the seal knife hardware, which is indicated by the vertical travel of the follower pin.

The 2-D rig allows an extensive survey of seal geometry and material effects on performance to be accomplished expeditiously at minimal costs in hardware fabrication, manpower, and schedule.

6.1.2 2-D Rig Modified for Flow Visualization

Aluminum side plates with 5.5 in. x 3.5 in. x 1/2 in. thick plate glass windows at the seal model viewing location, were substituted for the standard steel side plates used in normal performance testing, Figure 21. These two matching side plates were made for use with the schlieren optical imaging technique and a laser doppler velocimeter (LDV) system. The side plate windows are limited to a pressure difference of 15 psi, but this pressure level is adequate for rig

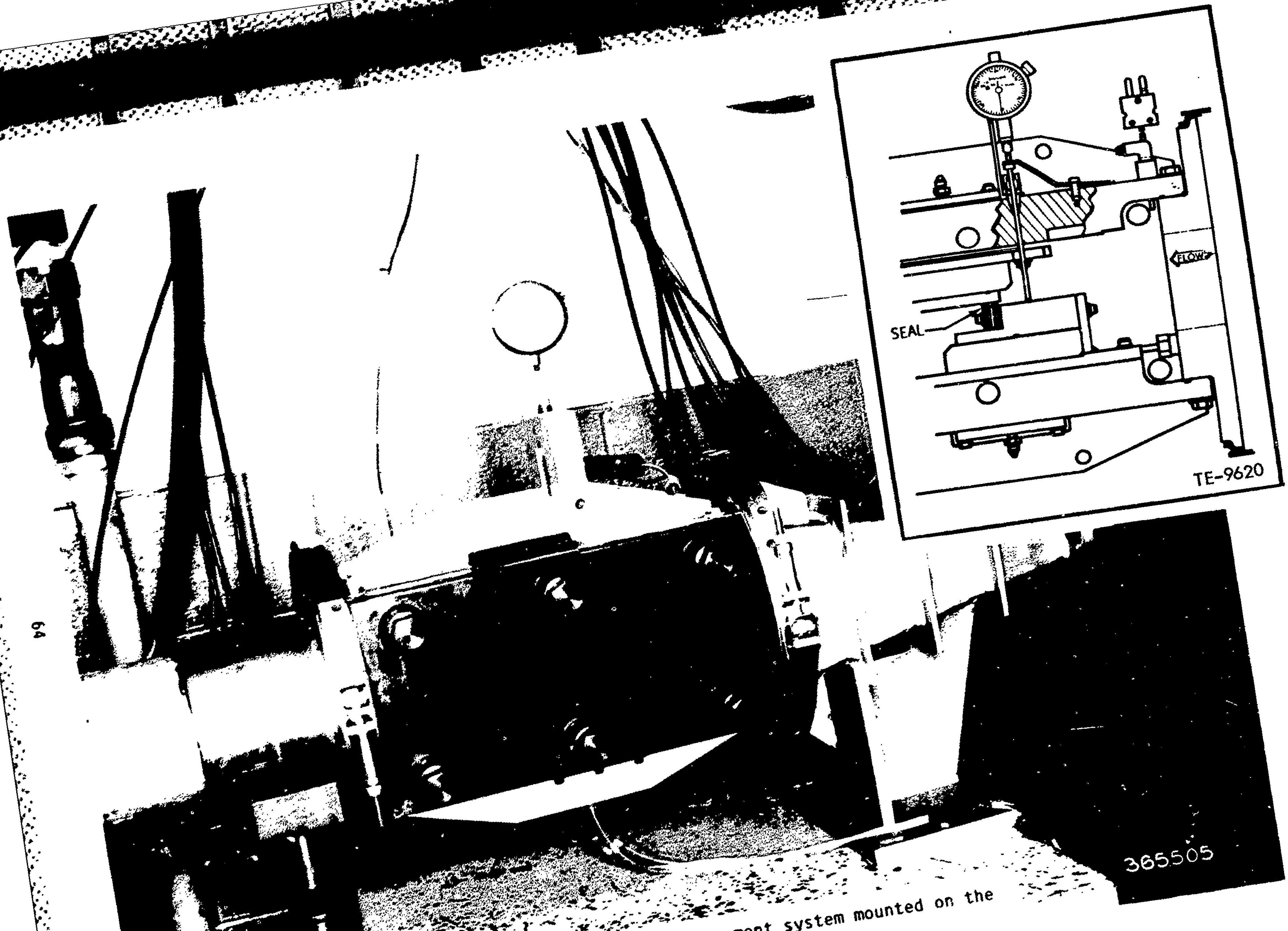

Figure 20. Clearance deflection measurement system mounted on the 2-D static rig.

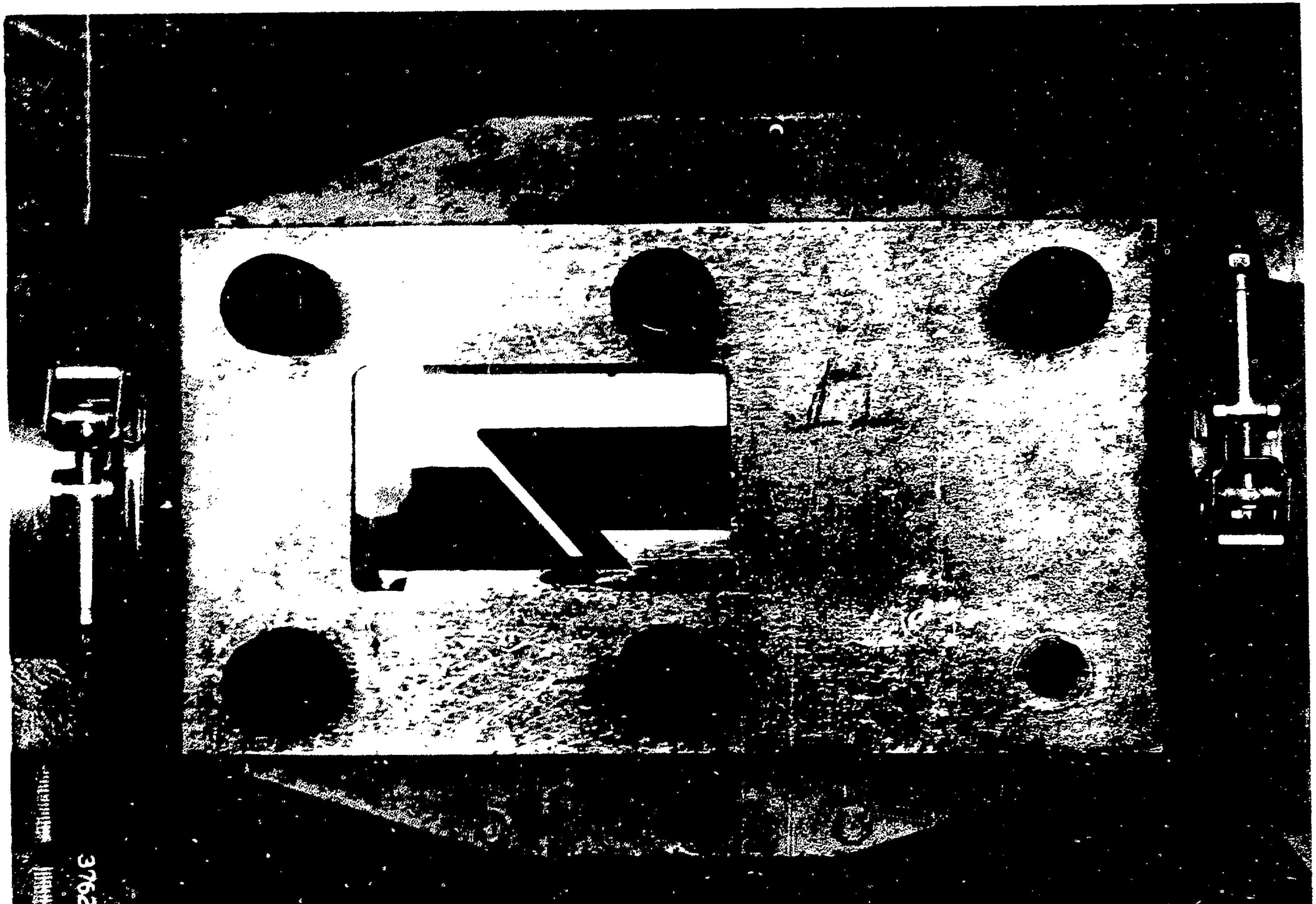

Figure 21. Two-dimensional (2-D) labyrinth seal test rig with plate glass windows in aluminum side plates.

testing with large-scale models. The conventional pressurized inlet plenum was employed for some of the schlieren testing, but better flow visualization and flow field velocity measurements were obtained with an atmospheric inlet and discharge evacuated by a steam ejector. Pressure ratios to 3.5 were obtained within the structural limits of the window glass with this pump-down arrangement.

Intraseal instrumentation requirements and flow visualization limitations placed constraints on the minimum model scale for the seal. The relatively small dimensions of the full-scale seal models prohibit accurate visualization of local flow-field phenomena. Therefore, a ten times (10X) full-scale seal model size was selected as the largest scale reasonably accommodated by the 2-D rig and air supply. Additional constraints on step height limited the size of stepped seal models to five times (5X) full-scale. Classical flow similarity theory governed the design which preserves the ratio of pressure forces to inertia forces and compressibility effects at the expense of variations of the ratio of viscous forces to inertia forces. Then the observations and measurements of the fluid dynamics in the large-scale seal will be comparable to those in the full-scale seal when flow similarity is independent of Reynolds number.

6.1.3 3-D Dynamic Rig

The terminology, 3-D (three-dimensional) dynamic test rig, is based on the circular geometry of the seal models. The test seals typically have a maximum diameter of 6.00 in. and can be run at rotational speeds to 30,000 rpm for the simulation of actual engine applications. The 3-D rig rotor is driven by an impulse turbine with speed control that is independent of the seal inlet pressure. Therefore, static performance (at 0 rpm) and the influence of knife tip speeds up to 785 ft/sec can be evaluated over a range of seal pressure ratio from 1.0 to approximately $0.32/\sqrt{CL}$. Figure 22 shows the 3-D rig installed in the research test facility. The principal subassemblies are identified in Figure 23.

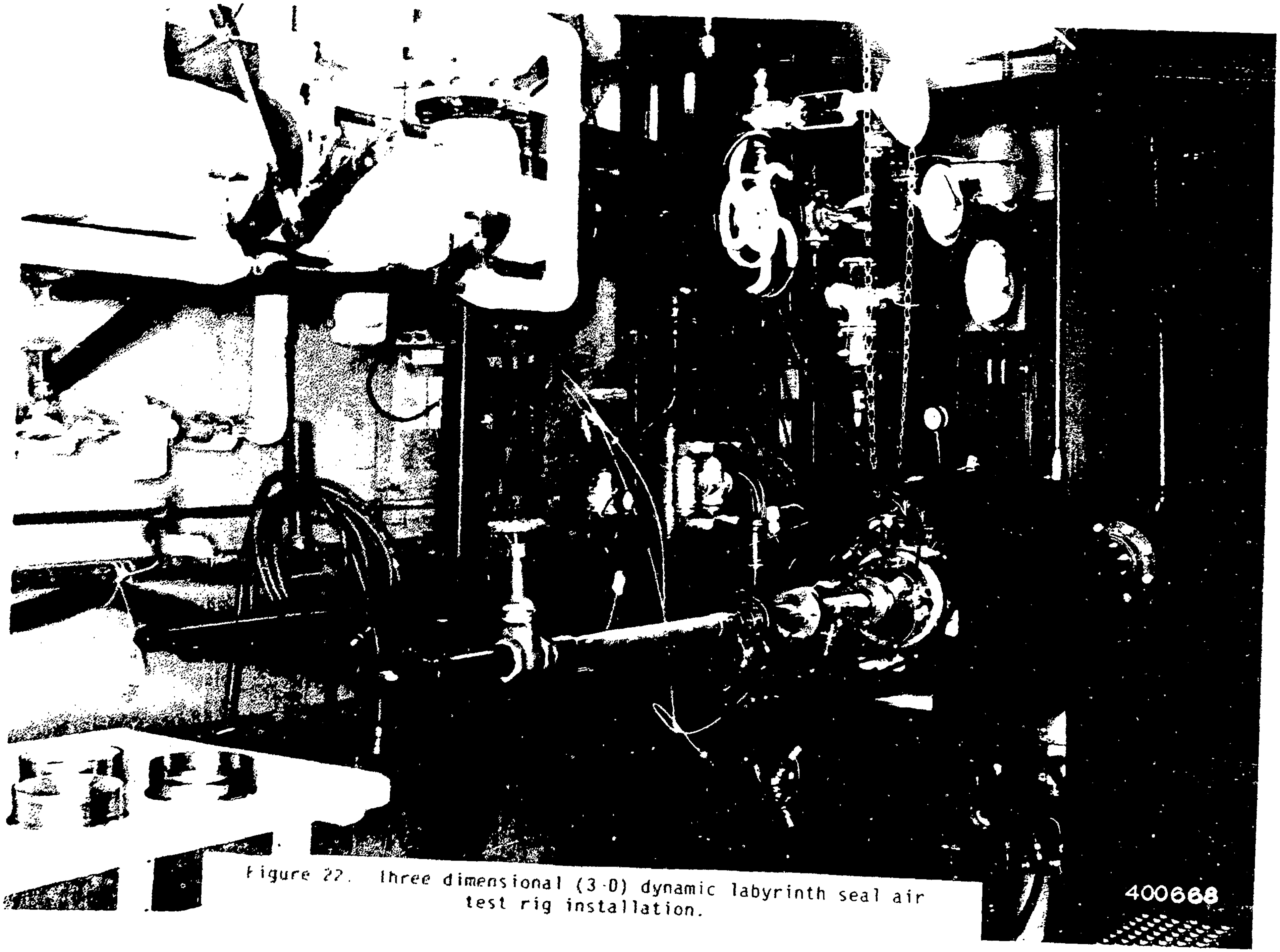

Figure 22. Three dimensional (3-D) dynamic labyrinth seal air test rig installation.

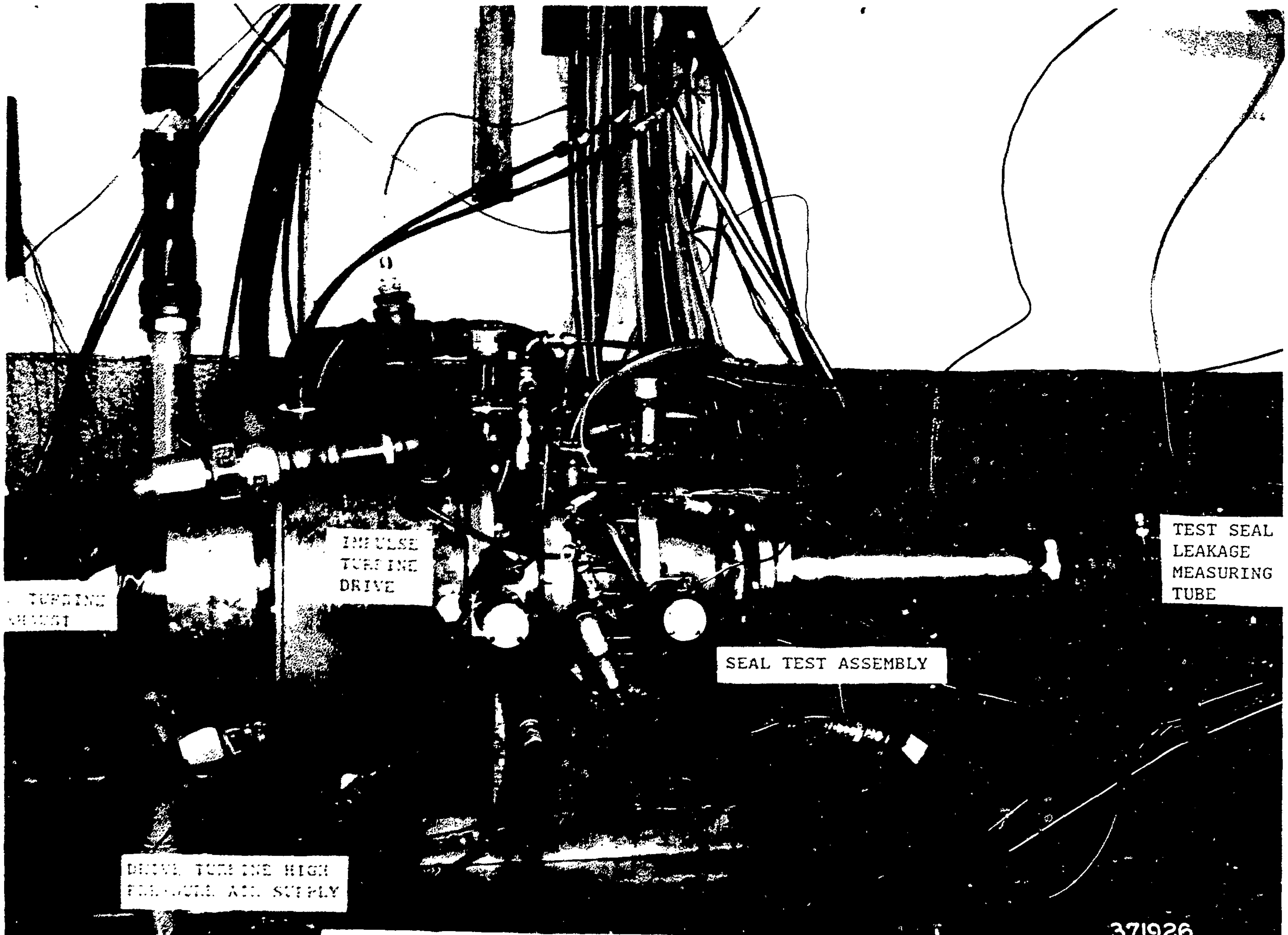

Figure 23. Three-dimensional (3-D) dynamic labyrinth seal air test rig components.

The seal knife geometry is normally tested on the rotor which is a unique combination of knife angle, number of knives, pitch, and knife height for a given flow direction and step height in the case of stepped seals. The matching stator is designed for a single clearance and can be reversed for the large-to-small diameter (LTSD) and the small-to-large diameter (STLD) flow direction testing in the case of stepped seals. Similarly, vertical knife stepped seal rotors can be tested in both flow directions. The distance-to-contact (DTC) for stepped seals or knife position over the land, as in the case of straight seals, can be varied by inserting shims behind the stator housing.

6.1.4 Test Rig Instrumentation

Comparable air temperature and static pressure instrumentation are used to determine the seal leakage performance in both the 2-D static rig and the 3-D dynamic rig. The 3-D rig employs additional temperature and static pressure instrumentation to define the tubine power produced during dynamic operation. Dynamic testing also requires some electronics to record rotor speed and to monitor two-degrees-of-freedom vibration levels at the seal test and turbine drive sections. Both rigs have been modified to accept instrumentation within the seal model.

6.1.4.1 2-D Rig Instrumentation

The instrumentation locations for the 2-D rig are shown schematically in Figure 24. Airflow through the seal model is determined with a standard ASME square-edge orifice with static radius taps.

Static pressures are measured upstream and downstream of the airflow orifice, at the seal inlet plenum, and at the seal downstream plenum. All of the large-scale seal models were instrumented with static pressure taps of 0.020 in. diameter located on the longitudinal centerlines of the knife-tips well away from any sidewall influence. Additional cavity static pressures were installed at appropriate axial locations in the same longitudinal plane.

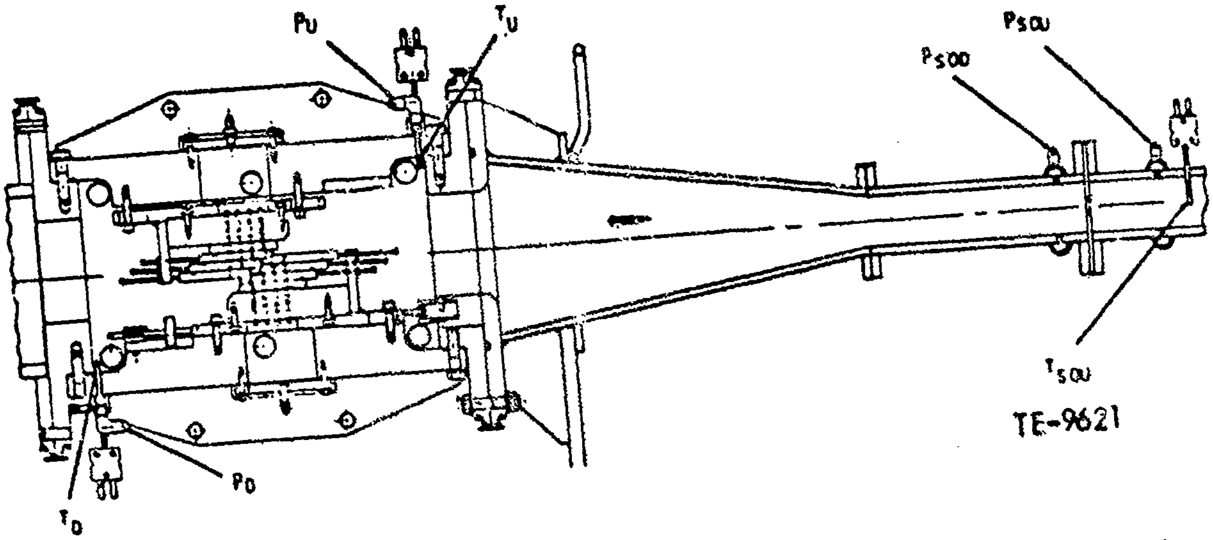

Figure 24. Typical two-dimensional static seal test rig instrumentation.

Air temperatures upstream of the airflow measuring orifice and upstream of the seal model are measured with shielded iron-constantan (I.C.) thermocouples. Two I.C. thermocouples are located downstream of the seal model: one thermocouple in the downstream plenum of the test section and one thermocouple in the exhaust pipe. All of the large-scale seal models were instrumented with additional I.C. thermocouples to measure air temperatures in the cavities and in the velocity carry-over jets. The cavity thermocouples were bare tipped. The carry-over thermocouples were shrouded and aspirated. All of the thermocouples were located out of line with the static pressure taps to provide reasonable isolation from wake spreading.

6.1.4.2 3-D Rig Instrumentation

The instrumentation locations for the 3-D rig are shown schematically in Figure 25. The airflow conditions required to define the seal leakage performance in the 3-D rig are the same as those required in the 2-D rig.

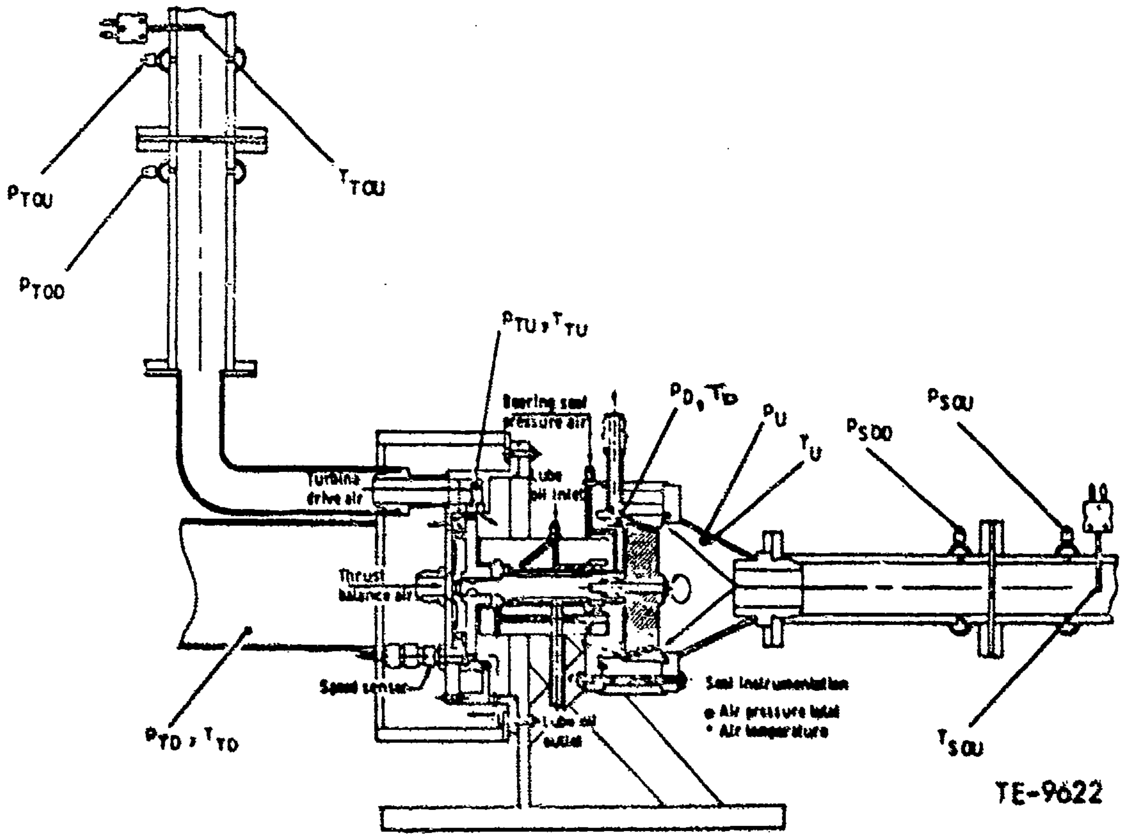

Figure 25. Typical three-dimensional dynamic seal test rig instrumentation.

A larger diameter ASME square-edge orifice is required for the 3-D rig which will pass three times the airflow rate as a similar 2-D rig seal configuration under the same pressure ratio.

The labyrinth seal upstream pressure is sensed on the diffuser wall well away from the local acceleration of the flow entering the seal and away from the vortex pumping of the rotor. The upstream I.C. thermocouple is deeply immersed near the axis of rotation of the 3-D rig rotor. The seal downstream pressure and temperature measurements are made in the discharge jet from the seal.

Five static pressure taps of 0.020 in. diameter were positioned in the smooth and rough stators, halfway between the knife tracks of the four knife straight seal, and on the same spacing ahead of and behind the rotor. No intraseal pressure instrumentation was installed in the stepped seal models or in the honeycomb seal models.

Additional data for the airflow conditions in the turbine section of the 3-D rig are necessary to define the power delivered to the rotor during dynamic testing. The turbine airflow is measured in the supply line with a standard ASME thin-plate, square-edge orifice. One additional thermocouple is required to measure turbine orifice inlet temperature.

Several operating parameters are monitored to ensure proper and safe dynamic testing in the 3-D rig. The most important of these from the standpoint of good performance measurement is the static pressure in the rotor thrust balance cavity. Here the thrust bearing load is controlled, which is crucial to valid power absorption data. Lubrication system pressures and temperatures are monitored as a safety precaution.

6.1.5 Data Reduction and Calculation Methods

The leakage performance of a labyrinth seal correlates on the airflow parameter,

$$\phi = \frac{w\sqrt{T_U}}{P_U \, A_t}$$

as a function of the seal pressure ratio, P_U/P_D, in the absence of Reynolds number or heat transfer effects. When the discharge pressure and inlet air temperature are approximately constant, the test Reynolds number is invariant at a given pressure ratio. The test air is delivered at essentially ambient temperature. The heat transfer influences are also minimized by the ambient temperature test fluid. The seal throat area is corrected from the buildup clearance measurements for rig case deflections in the 2-D rig and for rotor growth at dynamic conditions in the 3-D rig.

The data repeatability of the 2-D rig and the 3-D rig is typically $\pm 3\%$. Correlations between test results from the 2-D rig and the static 3-D rig are good with the principal variations attributable to the clearance area change through the stepped seal hardware for the 3-D rig.

When the local environment of an engine labyrinth seal is known in terms of air temperature (T_U) and the hot running clearance of the seal is specified so that the flow area can be calculated (A_t), then a unique iterative solution for compatible leakage flowrate (w), upstream pressure (P_U), and downstream pressure (P_D) is defined by the generalized seal performance curve ($w\sqrt{T_U}/P_U\ A_t$ versus P_U/P_D) in conjunction with the other restrictions in the seal flow circuit. The potential errors incurred by the extrapolation of this room temperature and barometric discharge pressure data to higher temperature and pressure engine environments are a function of Reynolds number and heat transfer effects. Generally, Reynolds number is most strongly influenced by model scale rather than kinematic viscosity of the air. Ordinarily heating of the seal leakage is influenced by rotor windage, seal pumping, and environmental heat transfer. Modeling of these secondary variables would require a full-scale engine seal with actual simulation of the thermal and pressure environment or an analytical model with this theoretical sophistication. The complication and expense of such rig testing makes the performance generalizing procedure the most feasible empirical approach. The Navier-Stokes Analytical Model could be used to calculate correction factors for Reynolds number and heat transfer effects in much the same manner that specific heat and humidity corrections have been developed for turbine engine performance parameters through aerothermodynamic cycle analyses.

6.2 PERFORMANCE TESTS ON FULL-SCALE LABYRINTH SEAL MODELS

Performance tests were run on selected full-scale models of straight and stepped labyrinth seals to extend the range and distribution of the geometric parameters for the Design Model data base, to evaluate the Design Model predictions for straight seal configurations outside of the conventional range of interknife cavity geometry, and to characterize the effect of open-cell honeycomb lands on the performance of straight and stepped seals.

One of the objectives of the literature survey was to identify the geometric parameters which affect the performance of labyrinth seals and to determine their ranges of application in the gas turbine industry. These parameters for straight and stepped seals are summarized below:

KN	number of knives
$K\theta$	knife angle
$\frac{KT}{CL}$	relative knife tip thickness
$\frac{KP}{CL}$	relative knife pitch
$\frac{KH}{CL}$	relative knife height
$\frac{KP}{KH}$	interknife cavity aspect ratio
$\frac{\epsilon}{2CL}$	land relative roughness

for stepped seals only

$\frac{SH}{CL}$	relative step height
$\frac{DTC}{CL}$	relative distance to contact
STLD or LTSD	flow direction

The tests required to fill voids in the available data base matrix were planned on the basis of these generalized geometric parameters. The performance data used in the multiple linear regression analysis for the Design Model development were correlated with seal geometry defined by these parameters.

A significant reduction in the number of tests required for the formulation of a comprehensive design model was made possible by the application of statistical analysis to model theory for compressible flow similarity.

6.2.1 Design Model Data Base Extension

Twenty-three performance tets were made over pressure ratios to 6 in the 2-D static labyrinth seal test rig. Of these, twelve were straight seal tests and eleven were stepped seal tests to augment the data base for the development of the Design Model. Table 12 lists the geometrical details of the seal configurations and the data voids filled by the tests. The performance data from each of the tests are presented graphically in Appendix B.

6.2.2 Effect of Interknife Cavity Aspect Ratio in Straight Seals

Komotori and Miyake (37) contend that an optimum interknife cavity aspect ratio exists for straight seals near a KP/KH.4. The earlier testing at Allison indicated a minimum straight seal leakage when the interknife cavity was square. The compilation of these somewhat conflicting empirical results into the data base for the Design Model was certain to skew the predictive capability away from the measured performance of the individual tests in the set. Consequently, an evaluation program was conducted to determine the capability of the Design Model to predict the performance of straight seals that were not in the data base which have a range of interknife cavity aspect ratios, $0.4 \leq KP/KH \leq 4.0$. A nominal envelope of relative seal geometries was covered by varying the clearance between 0.005 in. and 0.020 in. and testing two and four knives. Eighteen configurations of straight seals with vertical knives were tested in the 2-D rig. The geometric parameters of each test are listed in Table 13 with the evaluation of the Design Model prediction at a seal pressure ratio of 2.0. The plots of the seal performance measured and predicted are in Appendix C.

From these tests it was concluded that:

- o the Design Model predicts the flow parameter ϕ too high for low interknife cavity aspect ratios, $KP/KH < 1.0$.
- o the Design Model predicts the flow parameter ϕ too high for small clearance, $CL = 0.005$ in.

Table 12.

Full-scale labyrinth seal performance tests for the Design Model data base.*

Config Number	Rig	Seal Type	KN	KΦ deg	KT in.	Kβ deg	KH in.	KP in.	SH in.	CL in.	BTC in.	Flow Direction	Land Type	Justification
1	2D	Straight	1	50	0.015	19.1	0.200			0.010		Against KΦ	Smooth	KΦ
2	2D	Straight	4	50	0.015	19.1	0.200	0.200		0.010		Against KΦ	Smooth	KΦ
3	2D	Straight	1	70	0.015	19.1	0.200			0.010		Against KΦ	Smooth	KΦ
4	2D	Straight	4	70	0.015	19.1	0.200	0.200		0.010		Against KΦ	Smooth	KΦ
5	2D	Straight	2	90	0.025	20.0	0.200	0.200		0.005			Smooth	KT/CL KP/CL KH/CL
6	2D	Straight	2	90	0.025	20.0	0.200	0.200		0.010			Smooth	KT/CL KP/CL KΦ
7	2D	Straight	2	90	0.025	20.0	0.200	0.200		0.020			Smooth	KP/CL
8	2D	Straight	4	90	0.025	20.0	0.200	0.200		0.005			Smooth	KT/CL KP/CL KH/CL
9	2D	Straight	8	90	0.025	20.0	0.200	0.200		0.005			Smooth	KT/CL KP/CL KH/CL
10	2D	Straight	8	90	0.025	20.0	0.200	0.200		0.010			Smooth	KT/CL KP/CL KH/CL
11	2D	Straight	8	90	0.025	20.0	0.200	0.200		0.005			Rough	Land Type
12	2D	Straight	8	90	0.025	20.0	0.200	0.200		0.010			Rough	Land Type
13	2D	Stepped	2	50	0.015	8.0	0.280	0.400	0.120	0.020	0.194	STLD	Smooth	KΦ
14	2D	Stepped	2	70	0.015	8.0	0.280	0.400	0.120	0.005	0.194	LTSD	Smooth	KT/CL KP/CL KH/CL
15	2D	Stepped	2	70	0.015	8.0	0.280	0.400	0.120	0.027	0.194	LTSD	Smooth	KT/CL KP/CL KH/CL
16	2D	Stepped	6	70	0.015	8.0	0.280	0.400	0.120	0.005	0.194	LTSD	Smooth	KT/CL KP/CL KH/CL
17	2D	Stepped	6	70	0.015	8.0	0.280	0.400	0.120	0.010	0.194	LTSD	Smooth	KT/CL KP/CL KΦ
18	2D	Stepped	2	70	0.015	8.0	0.280	0.400	0.120	0.005	0.194	LTSD	Rough	Land Type
19	2D	Stepped	2	70	0.015	8.0	0.280	0.400	0.120	0.010	0.194	LTSD	Rough	Land Type
20	2D	Stepped	2	70	0.015	8.0	0.280	0.400	0.120	0.020	0.194	LTSD	Rough	Land Type
21	2D	Stepped	4	70	0.015	8.0	0.280	0.400	0.120	0.005	0.194	LTSD	Rough	Land Type
22	2D	Stepped	4	70	0.015	8.0	0.280	0.400	0.120	0.010	0.194	LTSD	Rough	Land Type
23	2D	Stepped	4	70	0.015	8.0	0.280	0.400	0.120	0.020	0.194	LTSD	Rough	Land Type

* Performance plots are in Appendix B, section B.1.1, p 203.

Table 13.
Effect of KP/KH, KN, CL on vertical knife straight seals at $P_U/P_D = 2.0$.

Test No.	KN	KT in.	KH in.	KP in.	CL in.	Φ_T Test	Φ_{DM} Design Model	Φ_{DM}/Φ_T
1	2	0.010	0.110	0.044	0.005	0.327	0.445	1.361
2	2	0.010	0.110	0.044	0.010	0.400	0.451	1.128
3	2	0.010	0.110	0.044	0.020	0.418	0.455	1.089
4	4	0.010	0.110	0.044	0.005	0.314	0.415	1.322
5	4	0.010	0.110	0.044	0.010	0.375	0.435	1.160
6	4	0.010	0.110	0.044	0.020	0.414	0.448	1.082
7	2	0.010	0.110	0.220	0.005	0.302	0.349	1.156
8	2	0.010	0.110	0.220	0.010	0.346	0.352	1.017
9	2	0.010	0.110	0.220	0.020	0.357	0.374	1.048
10	4	0.010	0.110	0.220	0.005	0.232	0.269	1.159
11	4	0.010	0.110	0.220	0.010	0.268	0.277	1.034
12	4	0.010	0.110	0.220	0.020	0.304	0.306	1.007
13	2	0.010	0.110	0.440	0.005	0.275	0.333	1.211
14	2	0.010	0.110	0.440	0.010	0.325	0.328	1.009
15	2	0.010	0.110	0.440	0.020	0.325	0.335	1.031
16	4	0.010	0.110	0.440	0.005	0.182	0.249	1.368
17	4	0.010	0.110	0.440	0.010	0.236	0.243	1.030
18	4	0.010	0.110	0.440	0.020	0.243	0.254	1.045

- the Design Model predicts the flow parameter ϕ very well at high interknife cavity aspect ratios, $KP/KH \geq 1.0$.
- the Design Model predicts the flow parameter ϕ very well for large clearances, $CL \geq 0.010$ in.

These test data imply that the minima predicted for the flow parameter of straight seals near a clearance of 0.010 in. may not exist, or at least occurs at a clearance less than 0.005 in. This abberation in the Design Model may be due to the difficulty in determining the actual clearance in seal models that are tested at clearances of 0.005 in. and less. The experimental uncertainty in seal data at small clearances is significantly greater than that obtained at clearances of 0.010 in. and greater.

6.2.3 Effect of Open-cell Honeycomb Lands in Straight and Stepped Seals.

Limited experimental data acquired during a NASA sponsored program (54) indicated that in four-knife straight seals:

- o honeycomb reduced leakage at large clearances,
- o honeycomb increased leakage at small clearances,
- o small cell size showed the least sensitivity to clearance.

A single test with an advanced four-knife stepped seal suggested that severe leakage penalties might be associated with the use of open-cell honeycomb in stepped seals. A slanted knife straight seal which was tested during an IR&D program showed that this seal leaked more with open 0.062 in. cell honeycomb than a similar straight seal with vertical knives. Dynamic testing with open-cell honeycomb lands in straight or stepped seals revealed a characteristic where leakage increased with knife tip speed, which is contrary to experience with solid-smooth lands. The apparently anomolous behavior of labyrinth seal leakage with open-cell honeycomb lands stimulated an interest in acquiring enough additional performance data to verify or refute the earlier observations.

The objective set for this program was to experimentally quantify the flow characteristics of straight seals with vertical and slanted knives over a conventional range of knife tip clearances. Three honeycomb cell sizes were investigated in the 3-D dynamic test rig, Table 14.

A sample of stepped seal performance was obtained with 0.062 in. open-cell honeycomb lands to verify the surprisingly high leakage rate observed during the NASA program. Vertical and slanted knives in both STLD and LTSD flow directions were tested in the 3-D dynamic rig as outlined in Table 15.

The data acquired from testing the five-knife straight seals are in excellent agreement with the previous NASA data, Figure 26. The performance ratio of honeycomb lands with respect to a baseline solid-smooth land provides a means for estimating the performance of labyrinth seals using honeycomb lands from the performance predictions of the Design Model. The test data from the vertical knife straight seals are compared with the predictions of the KTK model in Figures 27, 28, and 29. The Design Model performance correlated best

Table 14.
Performance tests on honeycomb lands in straight labyrinth seals.

Test	Kθ	KN	KT-in.	KP-in.	CL-in.	X-in.	b-in.
1	90°	5	0.010	0.100	0.005	0.031	0.075
2	90°	5	0.010	0.100	0.005	0.062	0.075
3	90°	5	0.010	0.100	0.005	0.125	0.075
4	90°	5	0.010	0.100	0.005	Solid	Smooth
5	90°	5	0.010	0.100	0.010	0.031	0.070
6	90°	5	0.010	0.100	0.010	0.062	0.070
7	90°	5	0.010	0.100	0.010	0.125	0.070
8	90°	5	0.010	0.100	0.010	Solid	Smooth
9	90°	5	0.010	0.100	0.020	0.031	0.060
10	90°	5	0.010	0.100	0.020	0.062	0.060
11	90°	5	0.010	0.100	0.020	0.125	0.060
12	90°	5	0.010	0.100	0.020	Solid	Smooth
13	70°	5	0.015	0.100	0.005	0.031	0.075
14	70°	5	0.015	0.100	0.005	0.062	0.075
15	70°	5	0.015	0.100	0.005	Solid	Smooth
16	70°	5	0.015	0.100	0.010	0.031	0.070
17	70°	5	0.015	0.100	0.010	0.062	0.070
18	70°	5	0.015	0.100	0.010	Solid	Smooth
19	70°	5	0.015	0.100	0.020	0.031	0.060
20	70°	5	0.015	0.100	0.020	0.062	0.060
21	70°	5	0.015	0.100	0.020	Solid	Smooth
22	50°	5	0.015	0.100	0.005	0.031	0.075
23	50°	5	0.015	0.100	0.005	0.062	0.075
24	50°	5	0.015	0.100	0.005	Solid	Smooth
25	50°	5	0.015	0.100	0.010	0.031	0.070
26	50°	5	0.015	0.100	0.010	0.062	0.070
27	50°	5	0.015	0.100	0.010	Solid	Smooth
28	50°	5	0.015	0.100	0.020	0.031	0.060
29	50°	5	0.015	0.100	0.020	0.062	0.060
30	50°	5	0.015	0.100	0.020	Solid	Smooth

Table 15.
Performance tests on honeycomb lands in stepped labyrinth seals.

Test	Flow direction	Kθ	KN	KT-in.	KP-in.	SH-in.	CL-in.	Xin.	b-in.
1	STLD	90°	4	0.010	0.300	0.120	0.020	0.062	0.090
2	STLD	90°	4	0.010	0.300	0.120	0.020	Solid	Smooth
3	LTSD	90°	4	0.010	0.300	0.120	0.020	0.062	0.090
4	LTSD	90°	4	0.010	0.300	0.120	0.020	Solid	Smooth
5	STLD	50°	4	0.015	0.300	0.120	0.020	0.062	0.090
6	STLD	50°	4	0.015	0.300	0.120	0.020	Solid	Smooth
7	LTSD	50°	4	0.015	0.300	0.120	0.020	0.062	0.090
8	LTSD	50°	4	0.015	0.300	0.120	0.020	Solid	Smooth

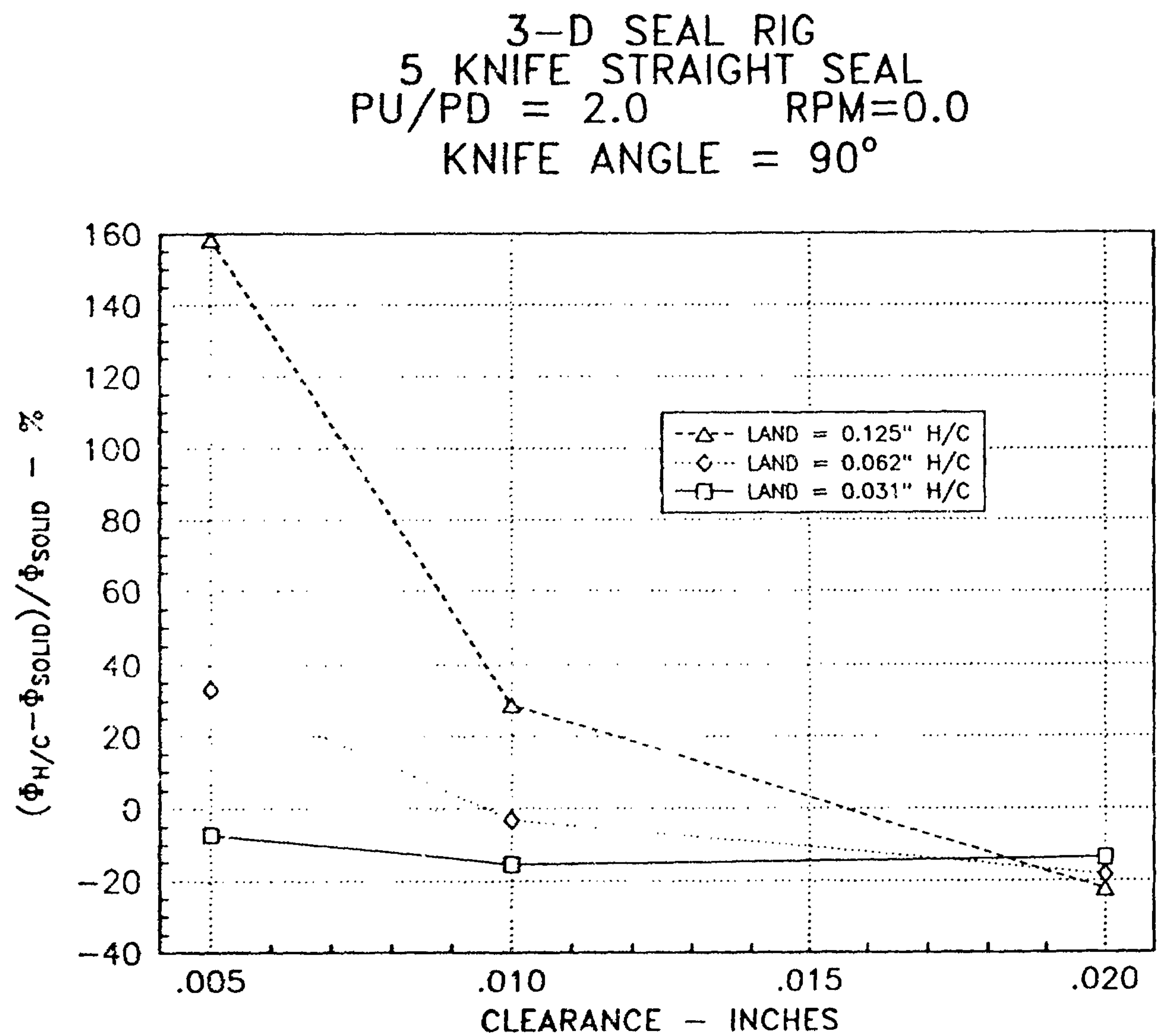

Figure 26. Effect of clearance on straight seals with open-cell honeycomb lands.

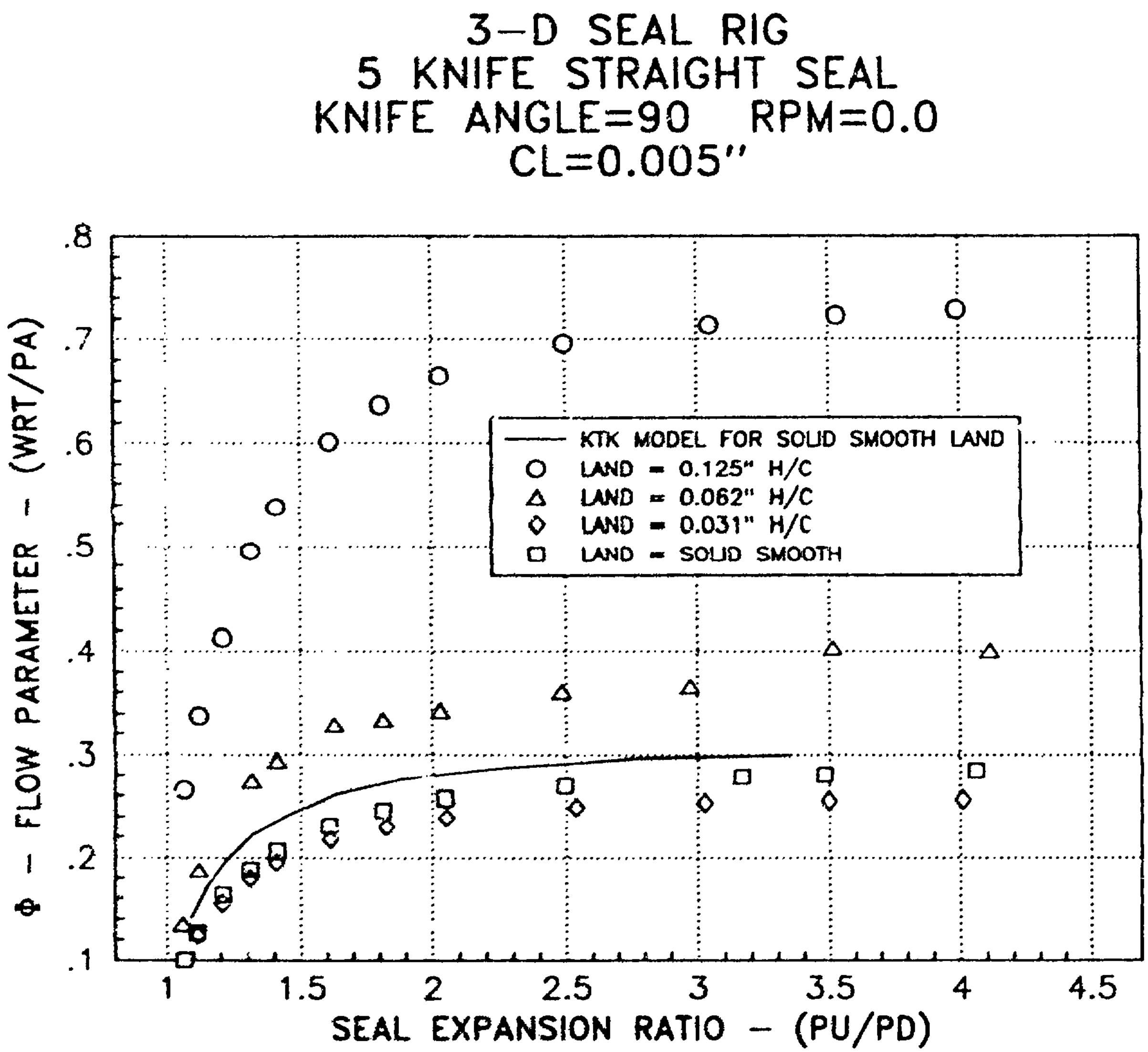

Figure 27. Design Model prediction compared with test data for a honeycomb straight seal at CL = 0.005 in.

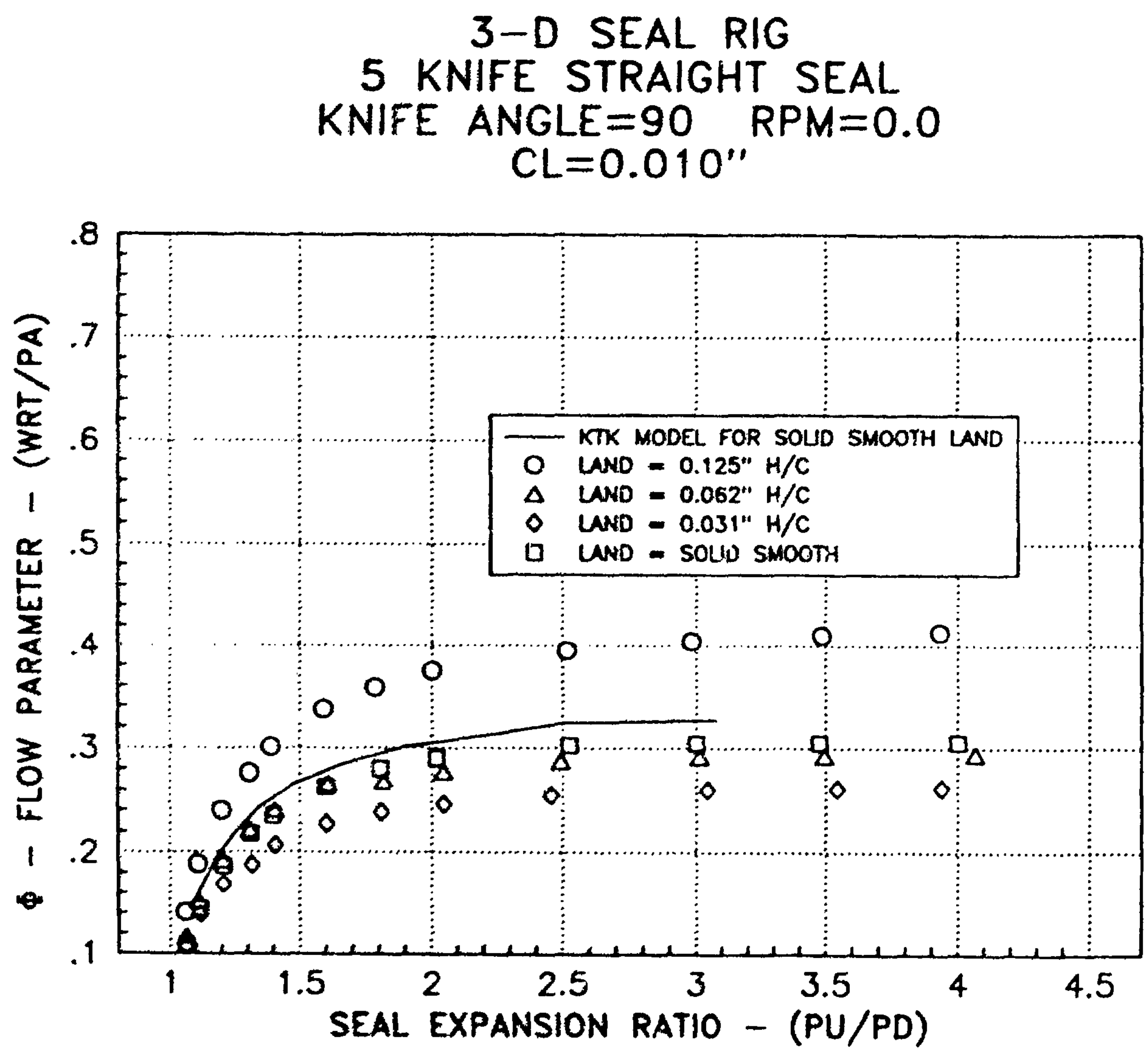

Figure 28. Design Model prediction compared with test data for a honeycomb straight seal at CL = 0.010 in.

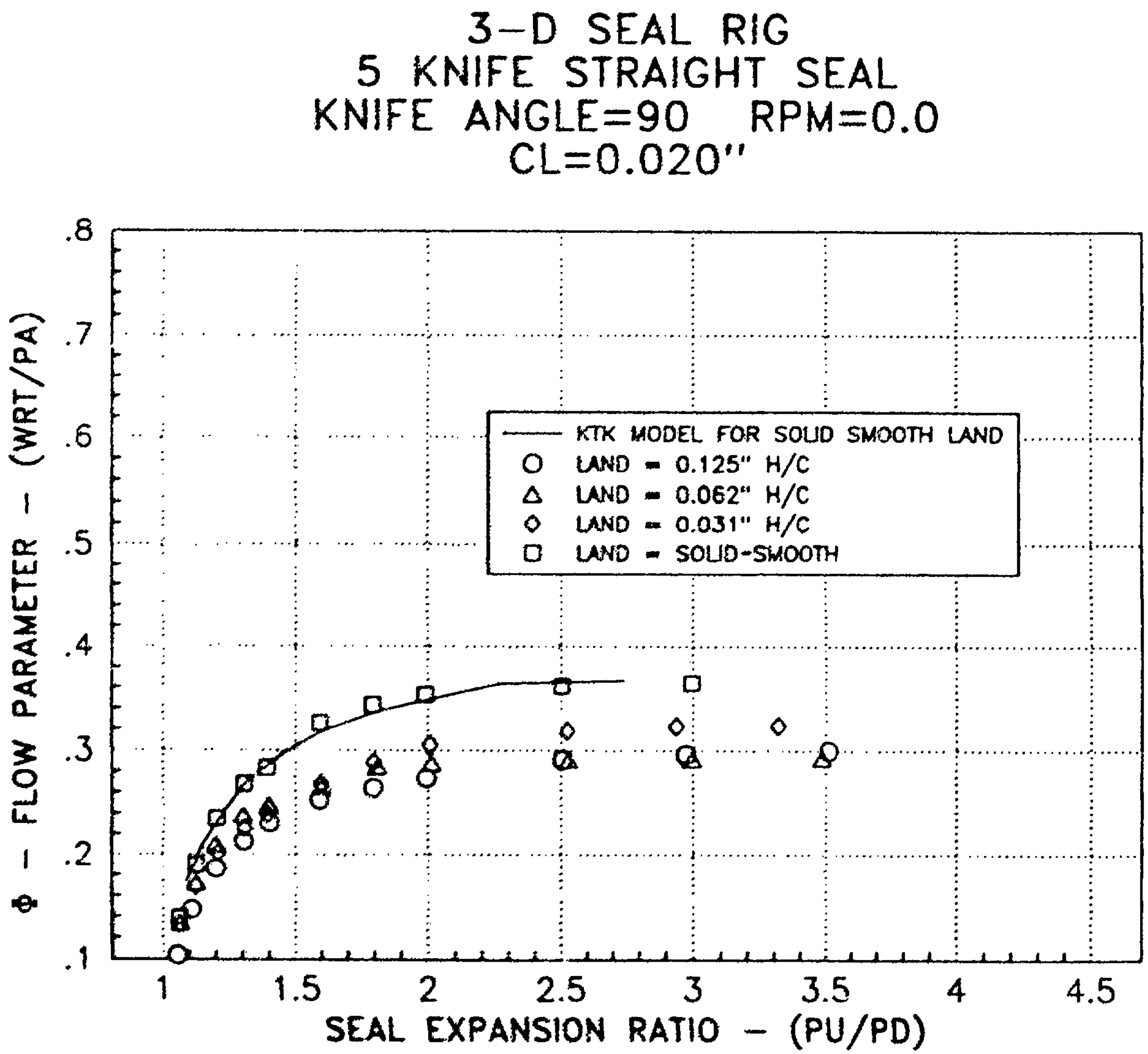

Figure 29. Design Model prediction compared with test data for a honeycomb straight seal at CL = 0.020 in.

with the test data for the largest clearance, CL = 0.020 in. Figures 30, 31, and 32 provide influence coefficients for honeycomb lands with vertical and slanted knives over a range of clearances. These plots indicate that the honeycomb lands leak more than solid-smooth lands as the relative cell size (X/CL) increases, probably due to the large surface porosity. However, leakage significantly lower than that obtained from a solid-smooth land can result at sufficiently small relative cell sizes, X/CL < 7, probably due to the effect of the roughness of the land surface. Slanting the knives of the straight seal generally reduces the influence of the large (X/CL > .8) and small (X/CL < .4) relative cell size honeycomb lands on the leakage performance. The leakage of the large relative cell size (X/CL > .8) honeycomb lands decreases with decreasing knife angle, and the leakage of the small relative cell size (X/CL < .4) honeycomb lands increases with decreasing knife angle. Crossover characteristics exist for the leakage of intermediate relative cell size (4 < X/CL <8) honeycomb lands. These characteristics can be verified by reference to Figures 33 and 34.

Knife rotation appears to have three distinct and essentially independent effects on the leakage performance of labyrinth seals: the thermodynamic effect of disk pumping on the inlet total temperature to the seal, the dynamic effect of the centrifugal forces on the seal flow-field structure, and the abrasive wear of the rotor knife tip and land. The abrasive wear effects result from the thermal and dynamic characteristics of the engine structure and the tribology of the seal materials. The disk pumping effect is influenced by the disk face geometry, wheel to stationary panel spacing, and through-flow (ventilation) in the wheel space. The rotational effects on the seal flow field are influenced by the geometry of the labyrinth seal and the surface structure of the stator land. The typical influence of rotation on conventional straight and stepped seal configurations produces between 5% and 10% leakage reduction at 785 ft/sec knife tip speed when compared with static performance. With a smooth land surface, the effect of rotation is small. However, with a roughened land or stepped seal configuration, the effect of rotation may be sizable.

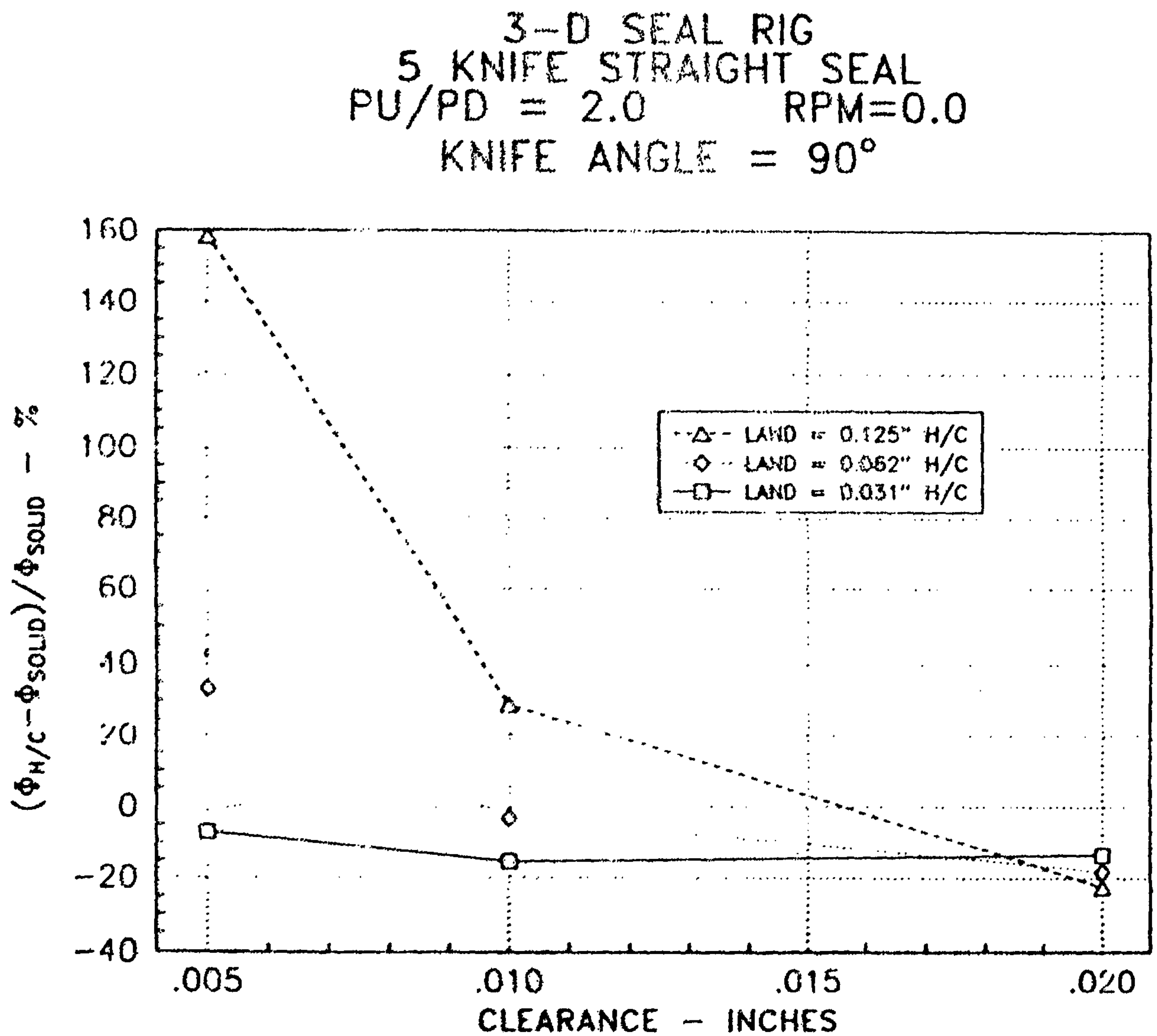

Figure 30. Influence coefficients for $K\theta$ = 90° straight seals with honeycomb lands.

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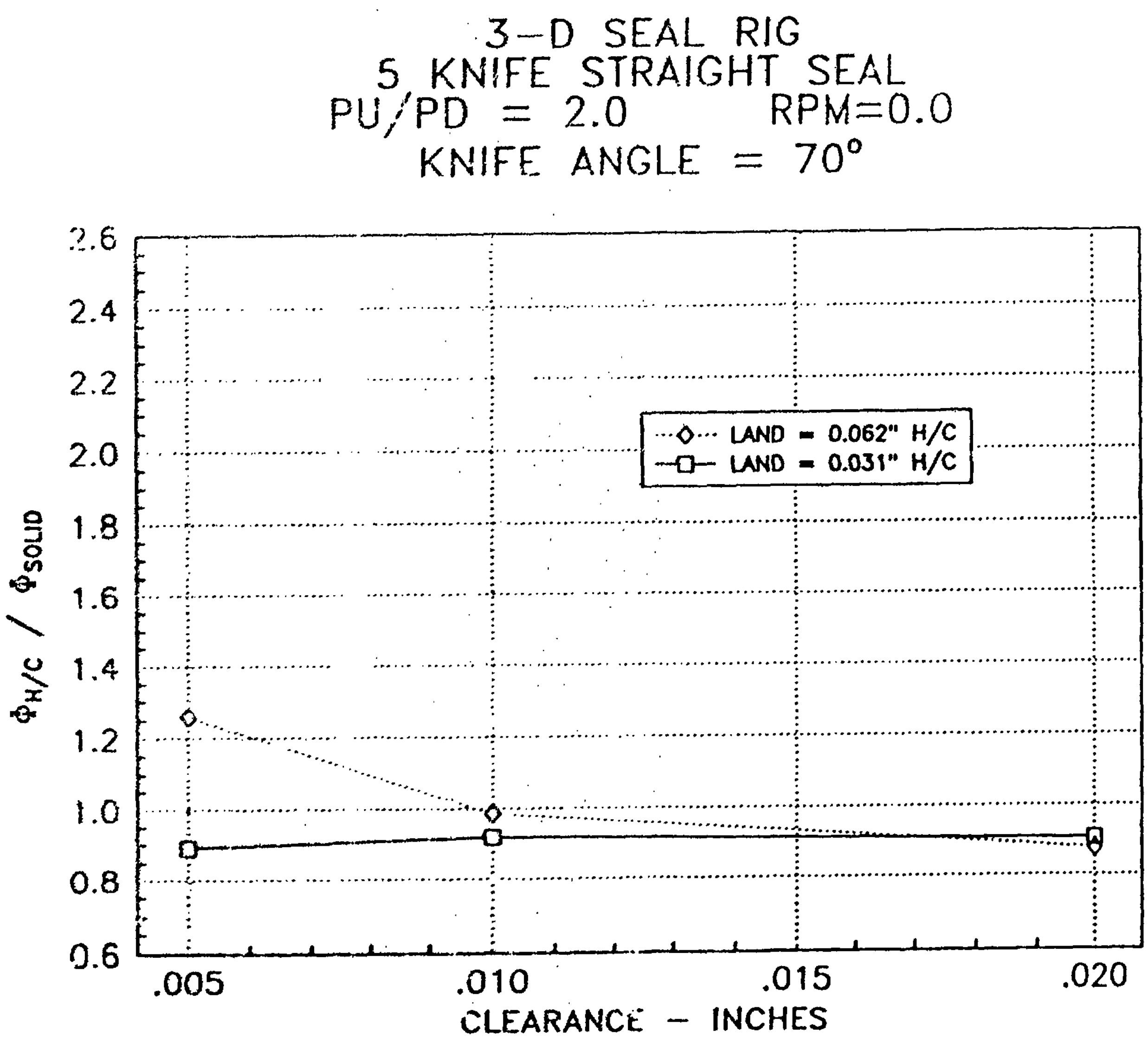


Figure 31. Influence coefficients for Kθ = 70° straight seals with honeycomb lands.

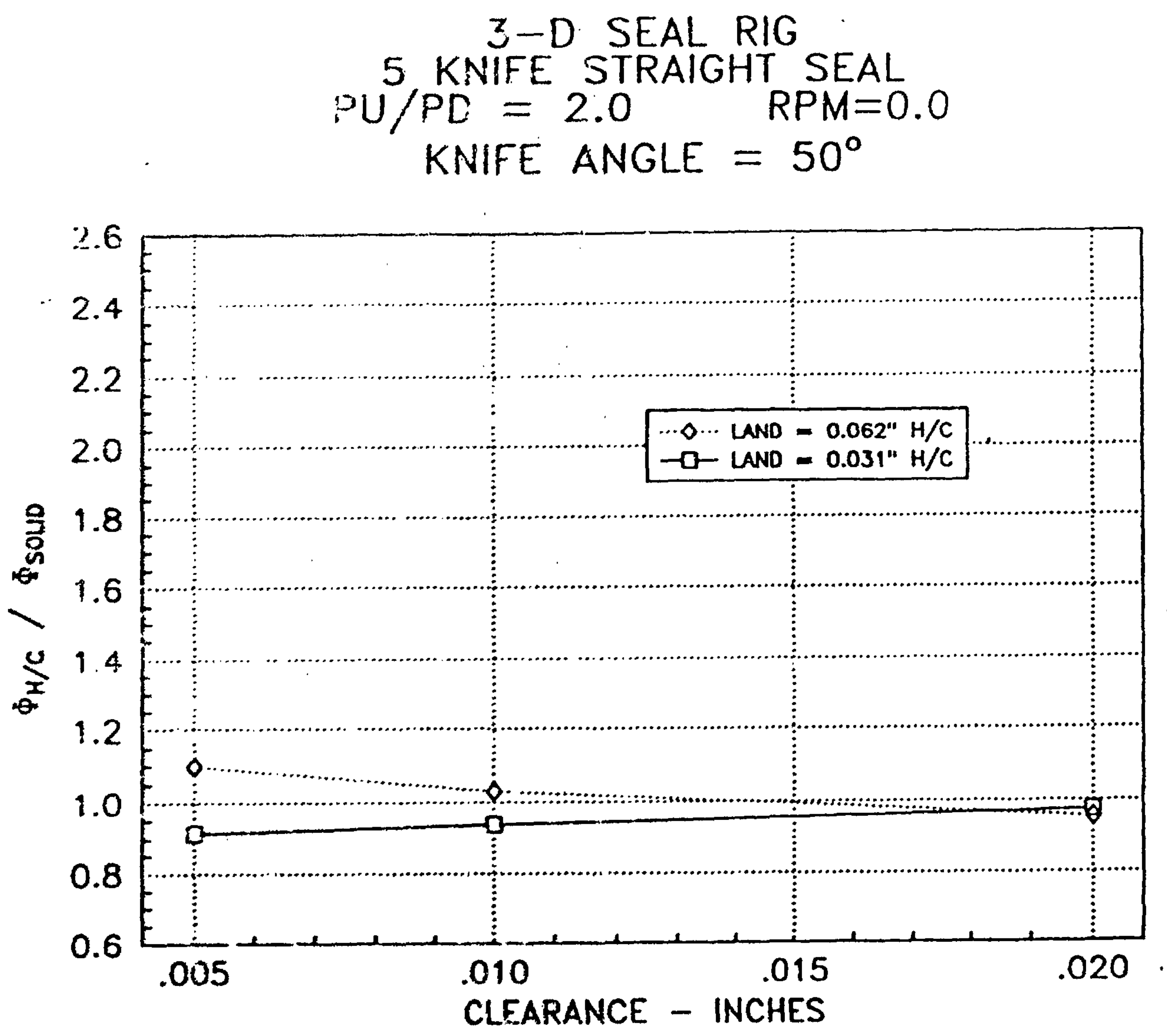


Figure 32. Influence coefficients for $K\theta$ = 50° straight seals with honeycomb lands.

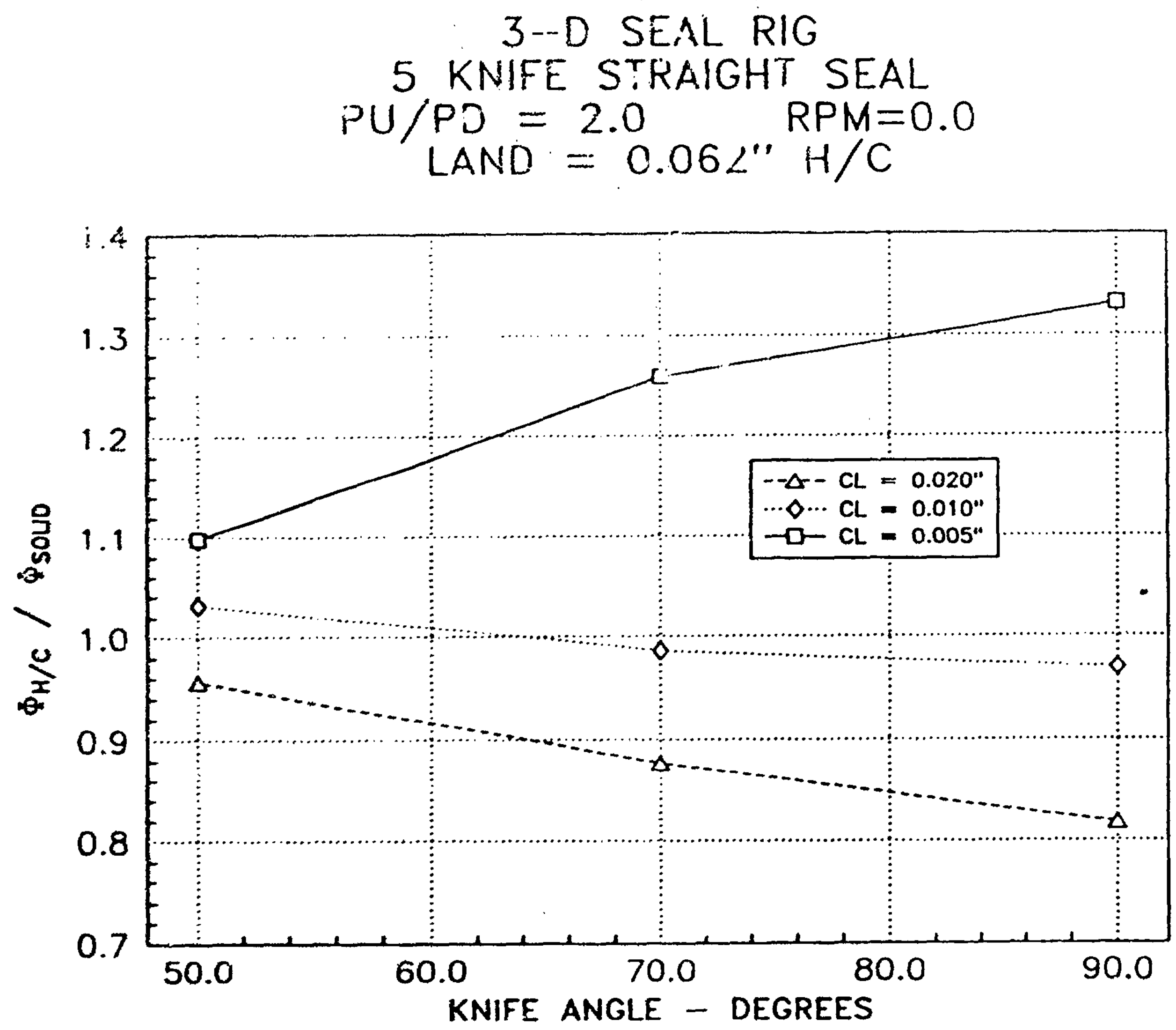


Figure 33. Effect of straight seal knife angle on 0.062 in. honeycomb lands.

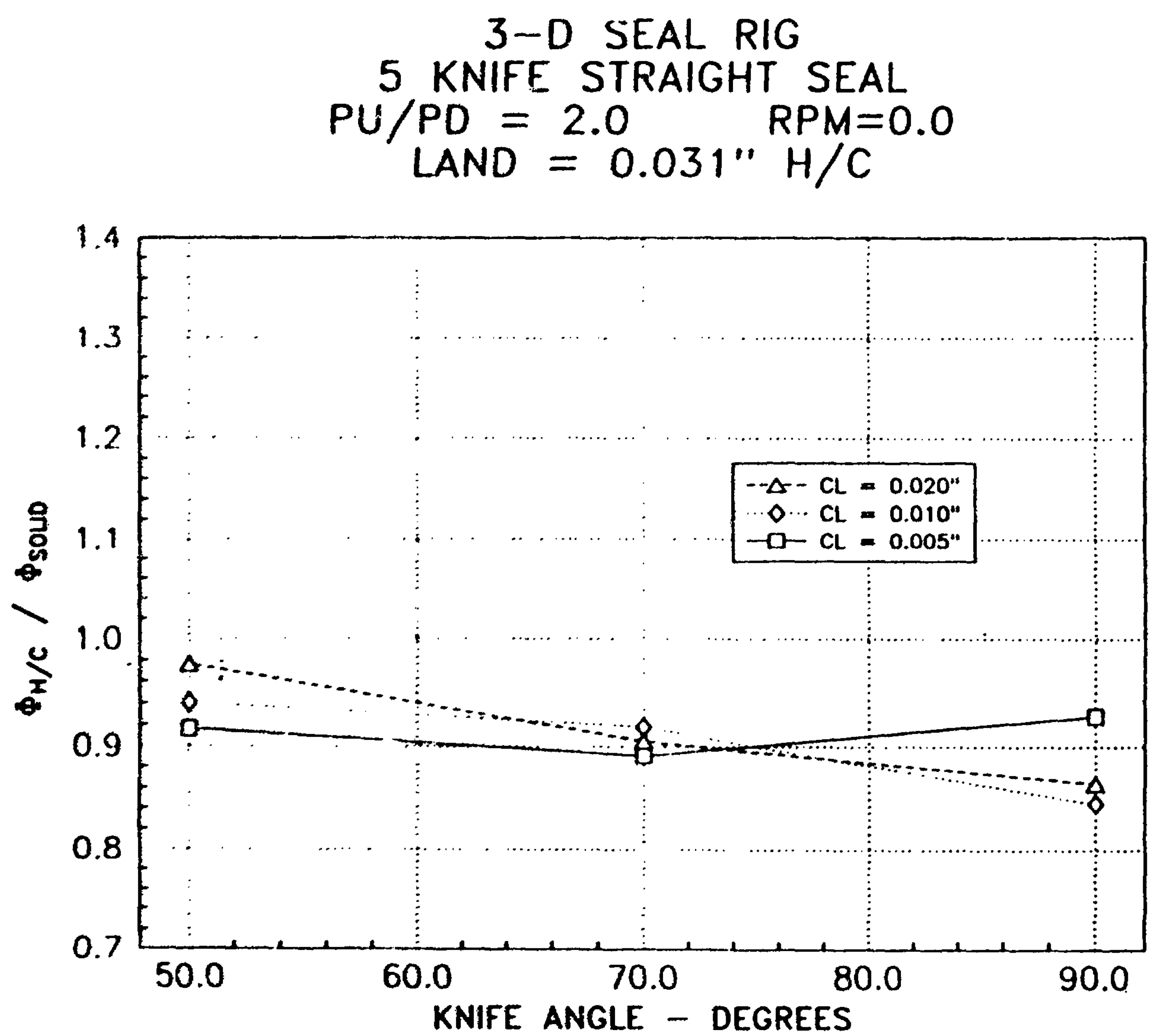


Figure 34. Effect of straight seal knife angle on 0.031 in. honeycomb lands.

Rotation of labyrinth seal knives reduces the flow parameter as knife tip speed increases near a solid-smooth land. The effect of open-cell honeycomb lands is similar in the roughness dominated domain at small relative cell sizes, Figure 35. However, as the relative cell size increases, the porosity effects become significant, and the flow parameter tends to increase with knife rotation, Figure 36. Then in the porosity dominated domain (X/CL > .8), the seal leakage increases with increasing knife tip speed, Figure 37. The slanted knives exhibit effects similar to those of the vertical knives on leakage performance as the knife tip speed increases.

A significant temperature rise is produced in the leakage flow passing through a high speed labyrinth seal with open-cell honeycomb lands. Table 16 lists the increase in leakage air temperature observed under dynamic test conditions with the straight seals in the 3-D rig. The solid-smooth land tests provide a baseline temperature rise resulting from windage off of the front face of the test rotor. The work required to swirl the flow between the rotor and a solid-smooth land is equivalent to a temperature rise of only a degree or two in the leakage flowrates at a $P_U/P_D = 2.0$. Consequently, the additional windage at a honeycomb land in the labyrinth seal results in a temperature rise in the leakage of as much as 20°F at $P_R = 2.0$. The temperature rise is a function of seal clearance and honeycomb size in addition to knife tip speed.

The results of the four-knife stepped seal tests corroborated the behavior observed in the NASA program for the replacement of a solid-smooth land with a honeycomb land using 0.062 in. cell size. When 0.062 in. open-cell honeycomb lands replaced solid-smooth lands in vertical or slanted four-knife stepped seals, the leakage increased from about 15% at static conditions to about 20% at a knife tip speed of 523 ft/sec. Figure 38 shows the performance comparisons between the stepped seals which were tested with solid-smooth lands and honeycomb lands. The apparent data inconsistency between the honeycomb land and solid-smooth land in the slanted knife stepped seal oriented for LTSD flow direction is explained by the inability of the knife tips to reach the honeycomb land inserts at Kθ = 50°. Therefore, the knives were running with a solid-smooth land in both tests.

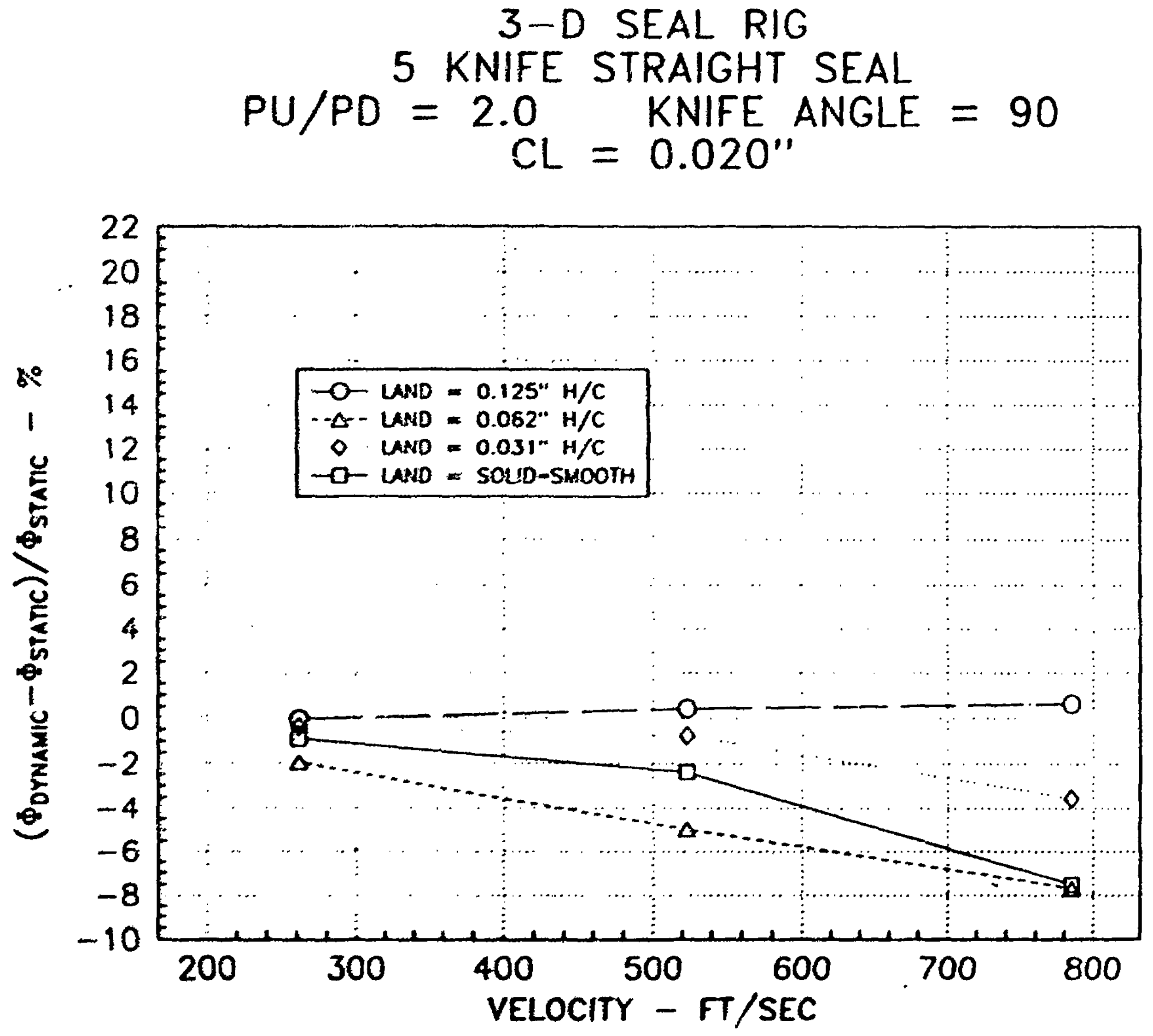


Figure 35. Effect of knife tip speed on the leakage of honeycomb lands at CL = 0.020 in.

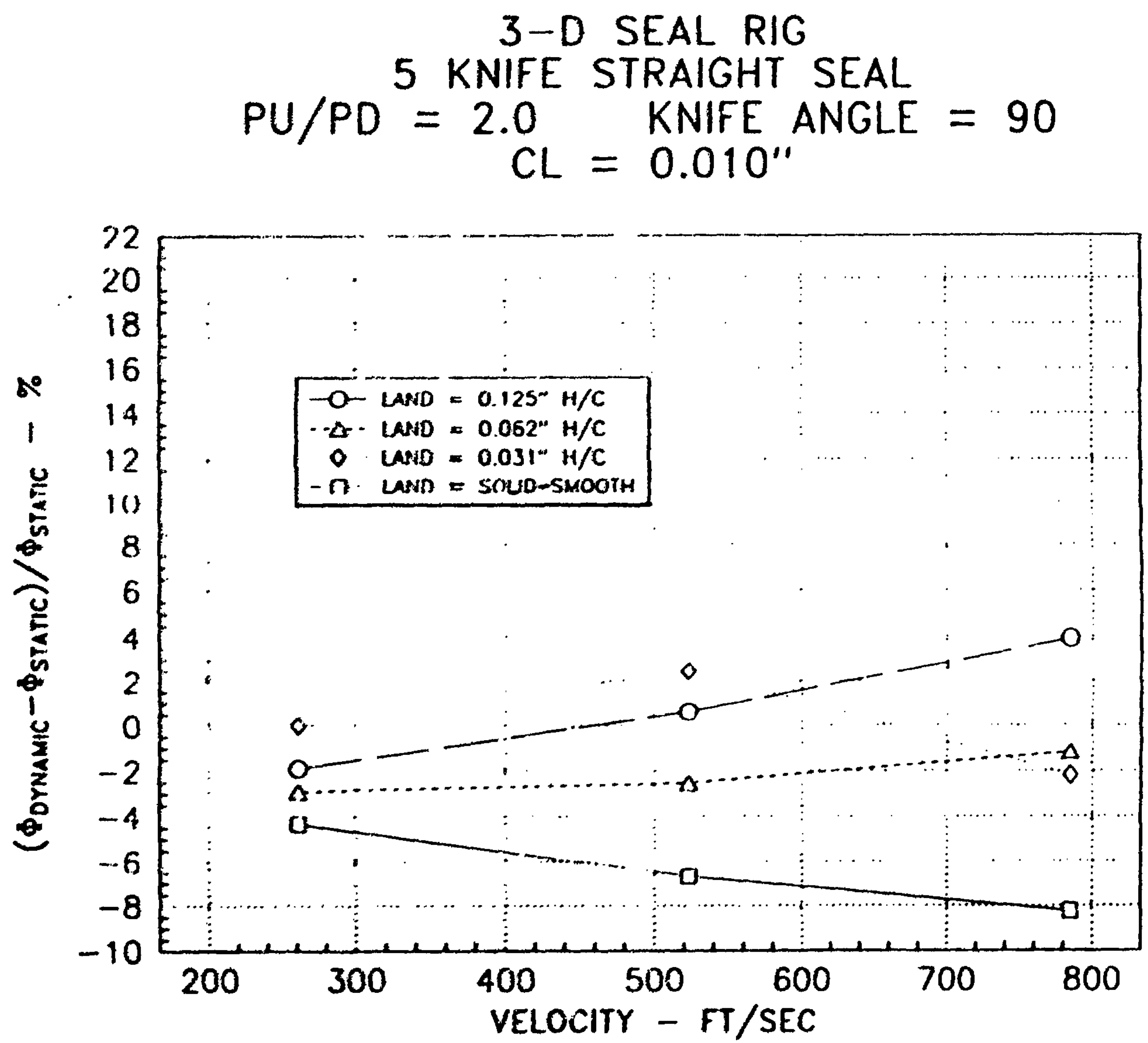


Figure 36. Effect of knife tip speed on the leakage of honeycomb lands at CL = 0.010 in.

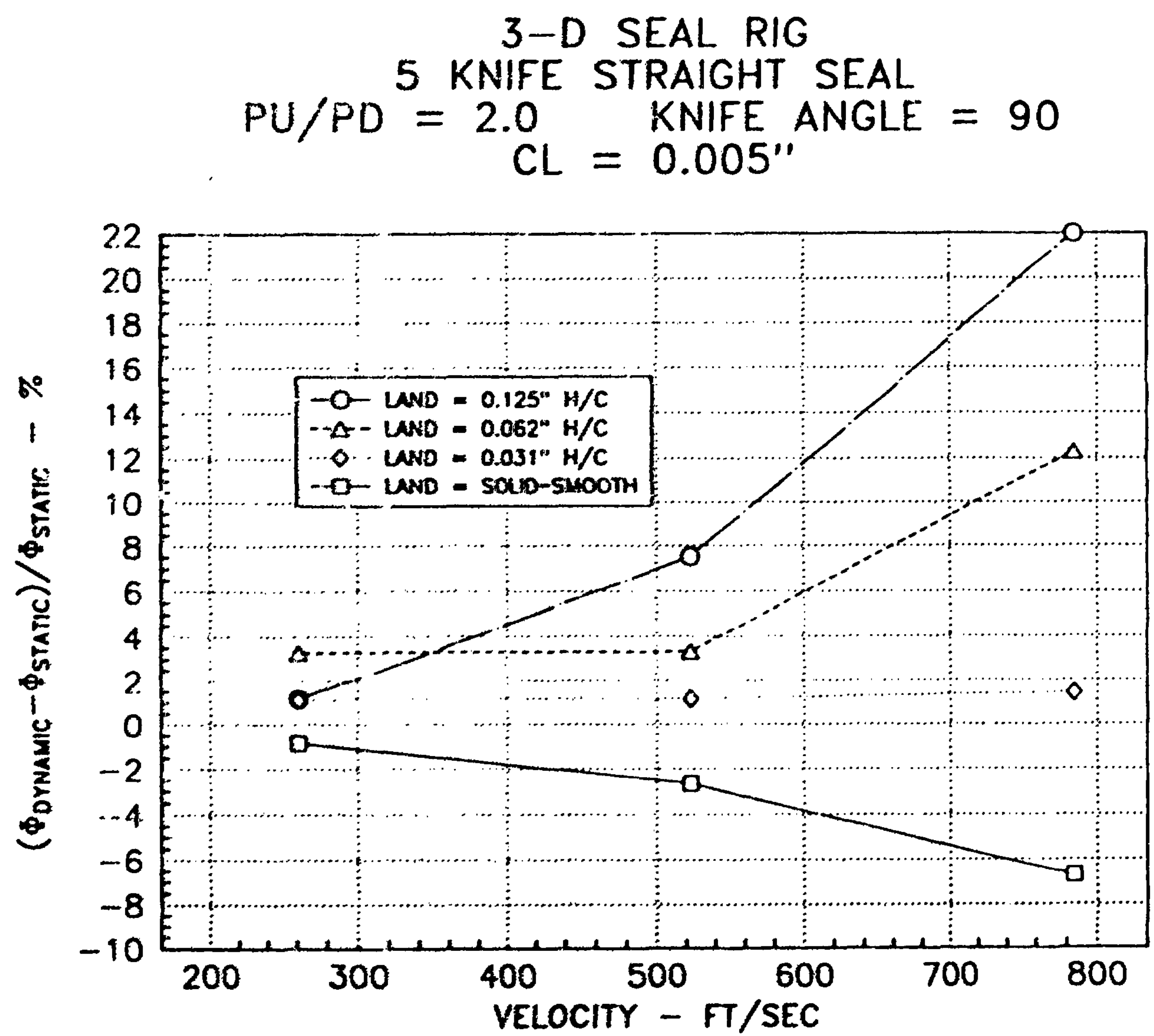
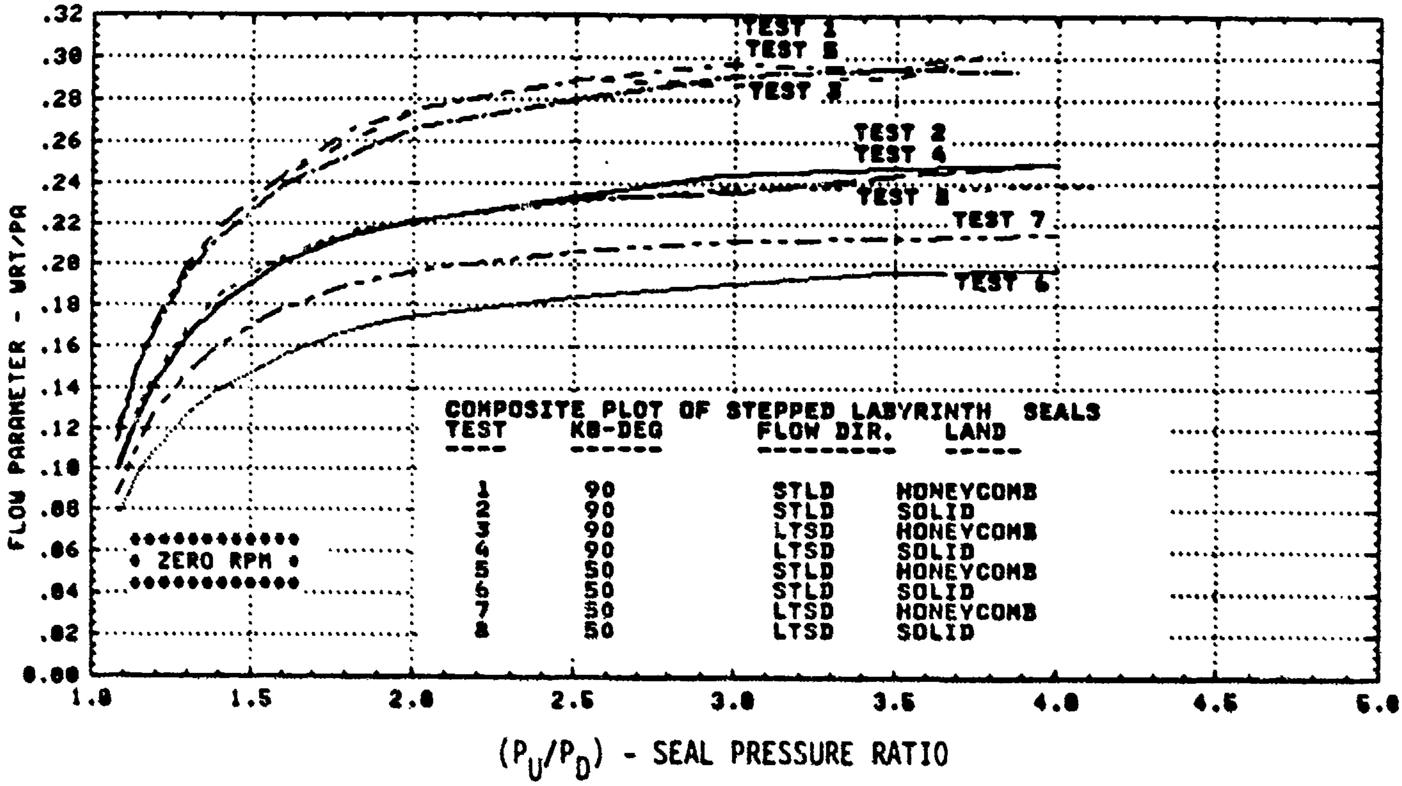


Figure 37. Effect of knife tip speed on the leakage of honeycomb lands at CL = 0.005 in.

Table 16.
Effects of honeycomb on temperature rise through a 5-knife straight seal at P_R = 2.0.

Kθ deg	CL in.	Land H/C type X, in.	ΔT, temperature rise through seal with rotation, °F V = 261 ft/sec	V = 523 ft/sec	V = 785 ft/sec
90	0.005	Solid	15.9	23.7	47.4
90	0.005	0.031	16.4	31.3	57.8
90	0.005	0.062	10.5	30.4	61.6
90	0.005	0.125	4.7	16.8	45.1
90	0.010	Solid	6.7	16.1	42.8
90	0.010	0.031	9.0	22.4	53.2
90	0.010	0.062	7.1	21.1	52.5
90	0.010	0.125	5.2	15.5	40.5
90	0.020	Solid	0.9	7.7	24.5
90	0.020	0.031	2.1	9.5	25.5
90	0.020	0.062	2.4	11.2	31.7
90	0.020	0.125	3.3	11.2	31.2
70	0.005	Solid	11.3	24.9	46.6
70	0.005	0.031	15.2	27.3	55.7
70	0.005	0.062	12.6	32.3	66.2
70	0.010	Solid	8.0	19.9	40.4
70	0.010	0.031	7.5	19.8	51.5
70	0.010	0.062	7.7	20.3	50.8
70	0.020	Solid	1.9	10.0	28.0
70	0.020	0.031	2.7	10.2	31.8
70	0.020	0.062	3.6	12.0	31.3
50	0.005	Solid	11.8	25.8	44.4
50	0.005	0.031	8.2	30.7	55.4
50	0.005	0.062	10.9	30.0	61.6
50	0.010	Solid	7.3	19.3	40.1
50	0.010	0.031	6.5	22.3	52.0
50	0.010	0.062	6.8	19.9	50.7
50	0.020	Solid	2.2	10.3	28.9
50	0.020	0.031	2.7	10.8	38.3
50	0.020	0.062	2.8	11.5	33.0



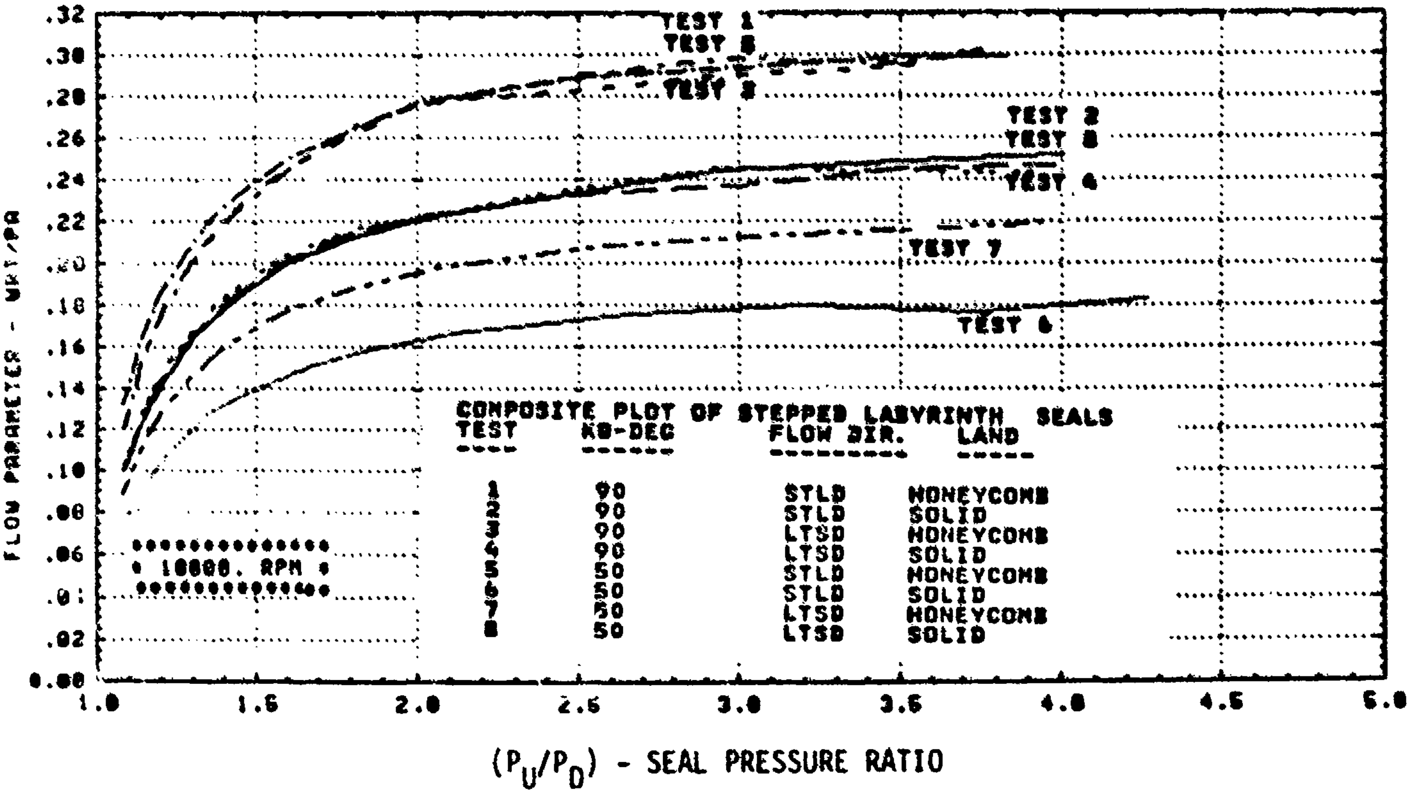
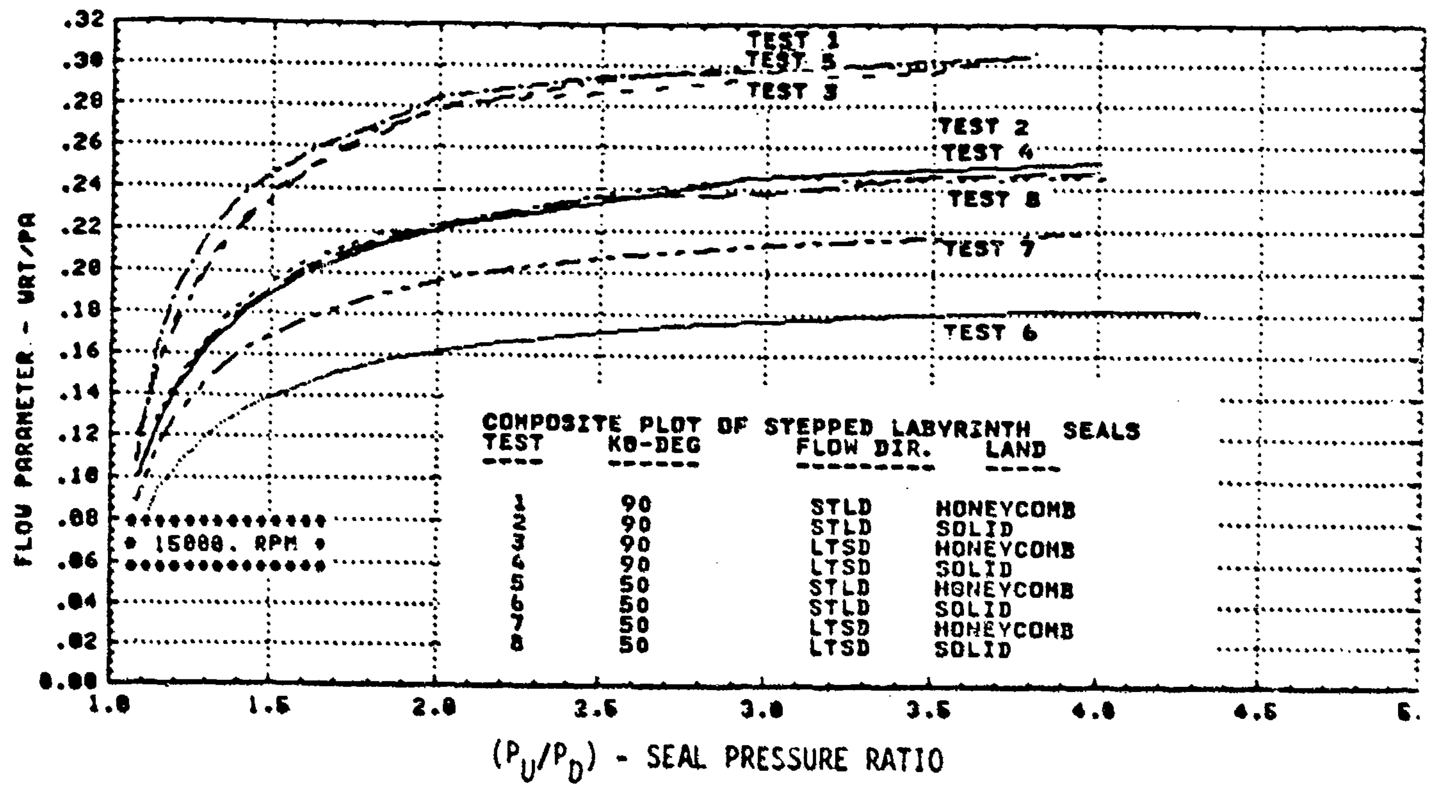


Figure 38. Effect of open-cell honeycomb lands on the performance of four-knife stepped seals.



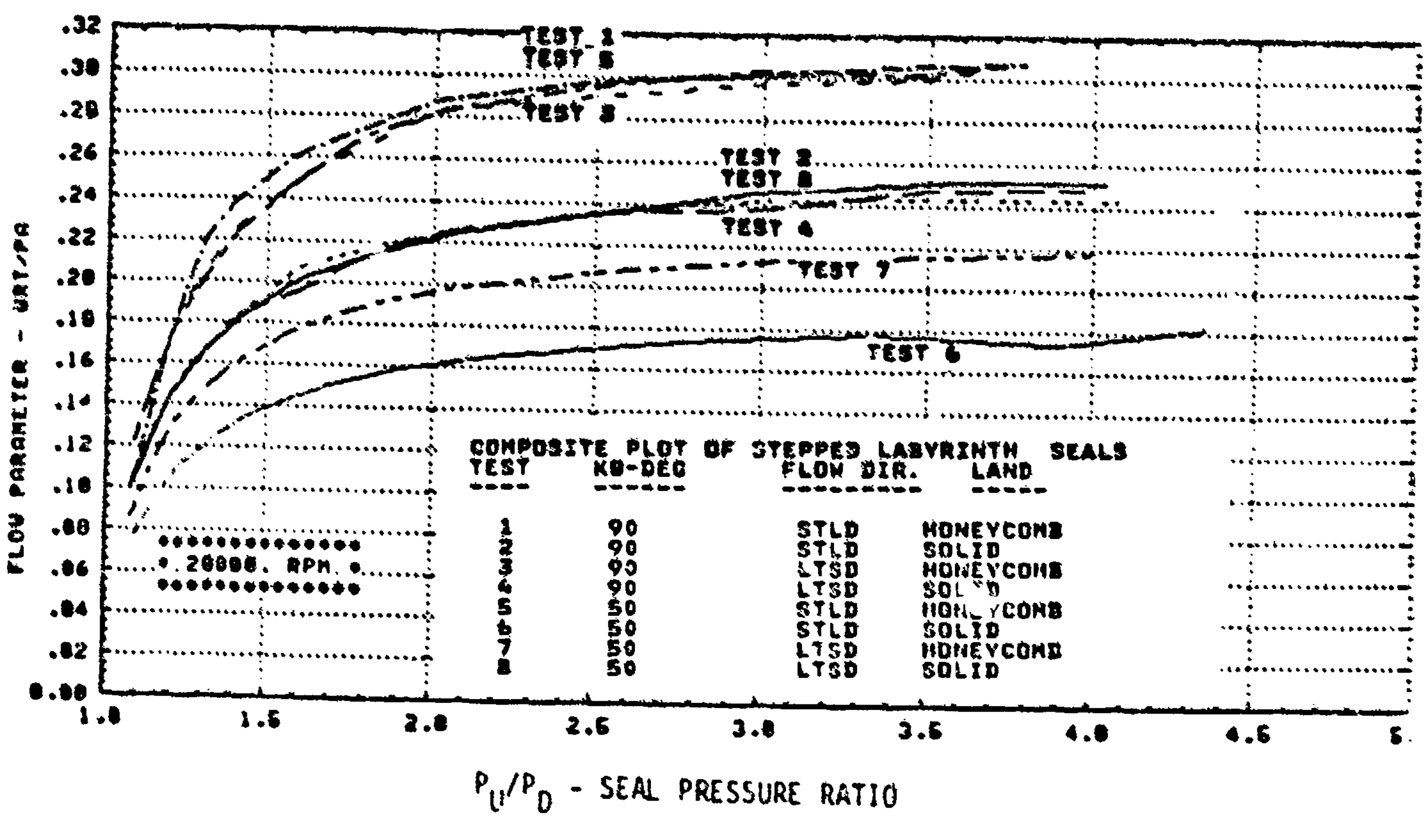


Figure 38. Effect of open-cell honeycomb lands on the performance of four-knife stepped seals. (continued)

The decreased leakage of the LTSD seal with $K\theta = 50°$ slanted knives and the honeycomb land is attributed to the wall roughness effect on the cavity flow between knives. This observation leads to the assumption that the increased leakage incurred by the use of the 0.062 in. open-cell honeycomb lands in stepped seals is due to the porosity effects at the knife-tips. Consequently, it may be that porosity effects dominate the flow at the knife tips while the roughness effects accrue to the overall gas path length in both straight seals and stepped seals.

The following conclusions can be derived concerning the design of straight seals with honeycomb lands:

- o Honeycomb lands may be employed effectively for abradability and for leakage control in straight seals. However, cell size is an important parameter for abradability and for aerodynamic effectiveness, which is a function of operating tip clearance. A large size honeycomb, e.g., 0.125 in., should be used only where tip clearance will be approximately 0.020 in. or more. Cell size should be kept to the minimum acceptable for abradability since that will minimize the sensitivity of performance to tip clearance.

- o Slanted knives are only advantageous at small operating clearances (near 0.005 in.) when used in conjunction with a more open cell size (0.062 in.) honeycomb. However, if abradability will permit the use of smaller cell size honeycomb (0.031 in. or less) slanting knives will not cause a performance penalty. Design simplicity would still require the general use of vertical knives in straight seals with honeycomb lands because slanted knives are most beneficial at clearances greater than 0.010 in.

Do not use open-cell honeycomb lands in stepped seals. Stepped seals excel at large clearances where abradability should not be a major design requirement. If abradability requirements necessitate honeycomb lands, design vertical knife straight seals with the largest permissible cell size for acceptable leakage performance.

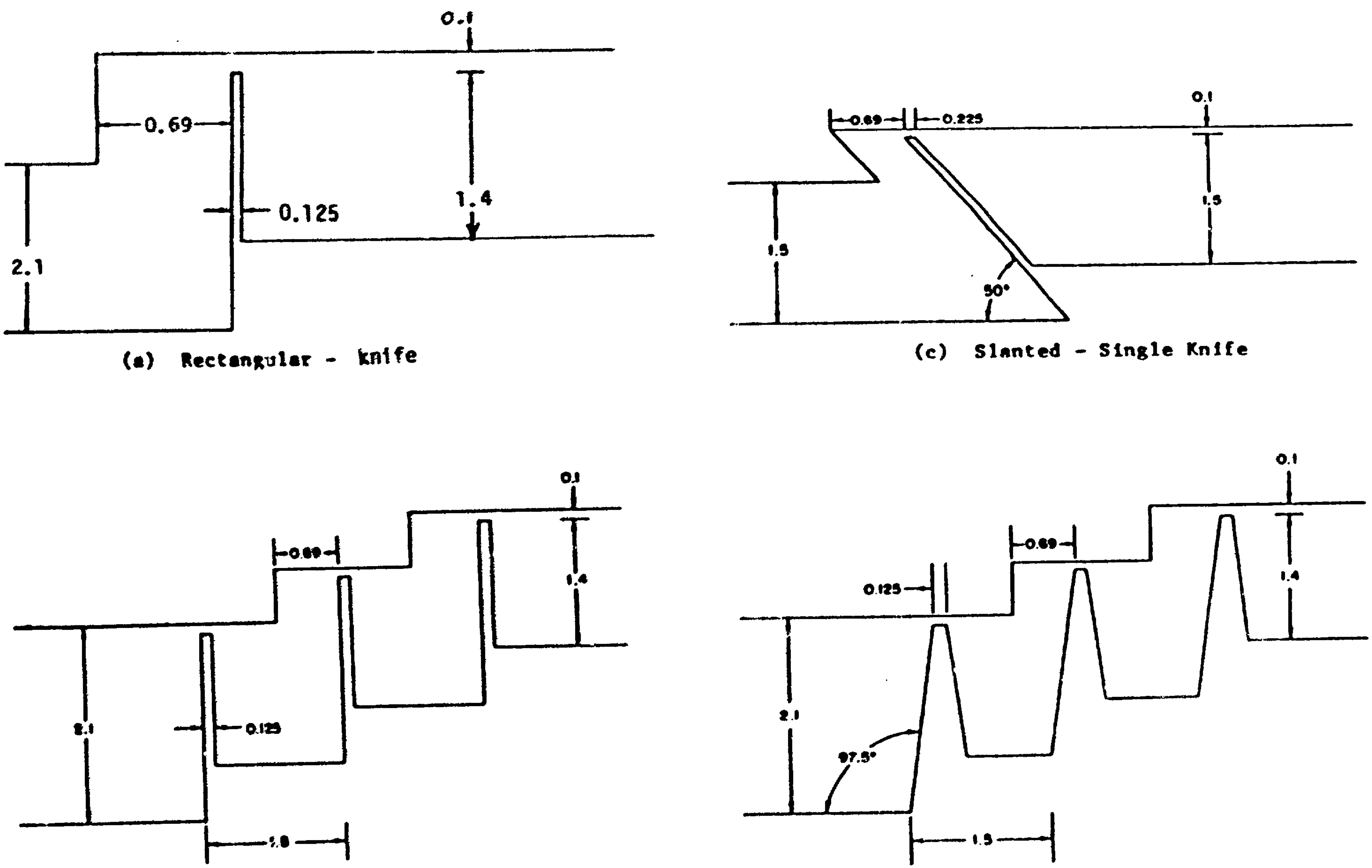
6.3 INTERNAL FLOW STRUCTURE

Fourteen seal-like configurations were subjected to a full Navier-Stokes flow analysis during the process of developing the Analysis Model code (66). Supporting tests to obtain leakage performance, qualitative flow field structure, and quantitative data for local flow field parameters were required to assist the analytical modeling and to evaluate the predictions of the Analysis Model. Large-scale models of these straight and stepped seals were required for definitive flow visualization and flow field measurements. Seven of the seal configurations studied with the Analysis Model were fabricated and tested in the 2-D rig, Figures 39 and 40. Leakage performance, local flow field pressure and temperature, and local velocity distributions were measured in these seals.

A modified schlieren technique was developed for the visualization of the subsonic flow structure in the large-scale seal models. The technique is dynamic in nature and relies primarily on the motion of the flow for structural definition. The flow fields for the seven reference seal configurations were recorded on video tape for qualitative comparison with the carry-over and recirculation structure calculated by the Analysis Model. In addition, sixteen flow visualization tests were made to determine the way in which relative knife edge sharpness (KR/CL) and interknife cavity aspect ratio (KP/KH) influence the structure of the flow field in vertical knife straight seals.

6.3.1 Large-Scale Seal Performance

Performance tests, which were separate from the flow visualization tests, were conducted on the nine configurations of the large-scale seal models defined in Table 17. In addition to providing leakage characteristics for the overall performance comparisons in Ref (66), these 2-D rig models were instrumented for internal temperature and static pressure measurements, which will be discussed later. The straight seals were designed on a scale ten times (10X) the size of the nominal full-scale seals. The stepped seals were limited to five times (5X) the nominal full-scale dimensions by the test section height of the



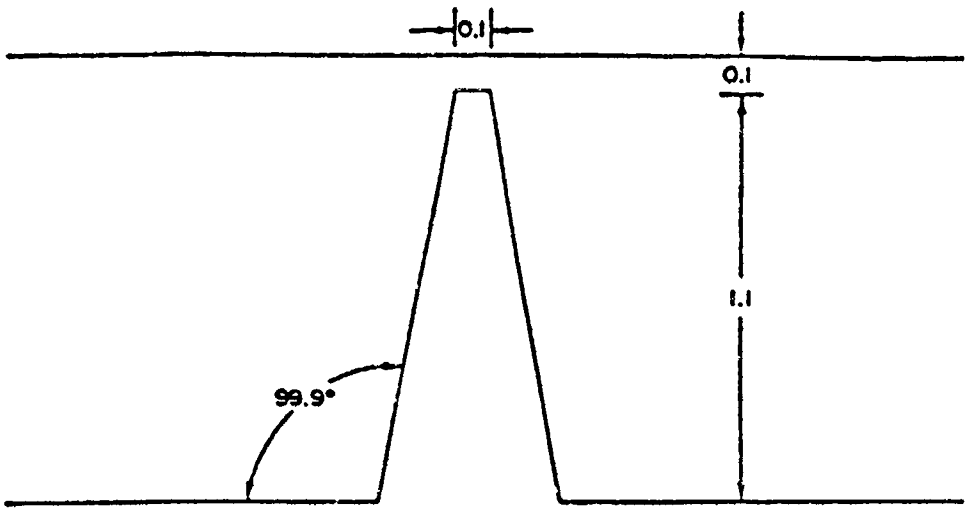
(a) Rectangular - knife

(c) Slanted - Single Knife

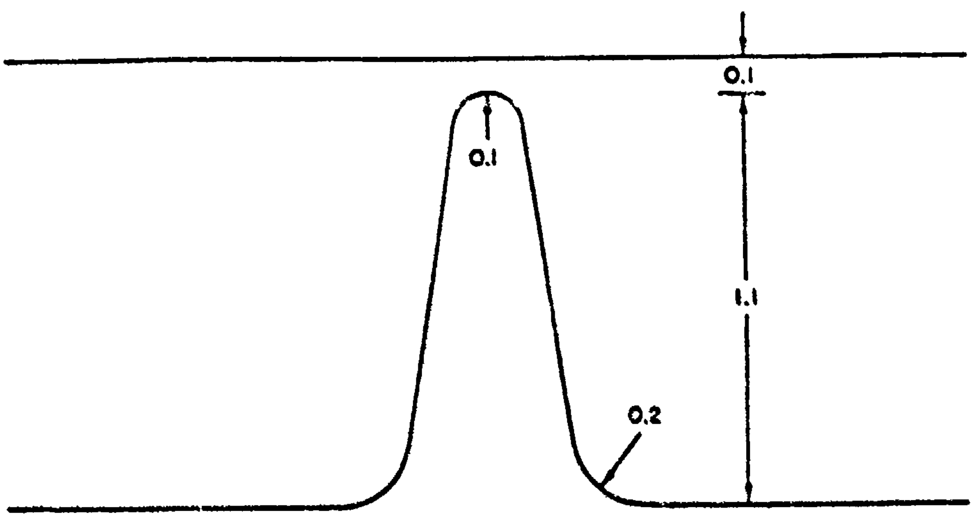
(b) Rectangular - Three Knives

(d) Tapered - Three Knives

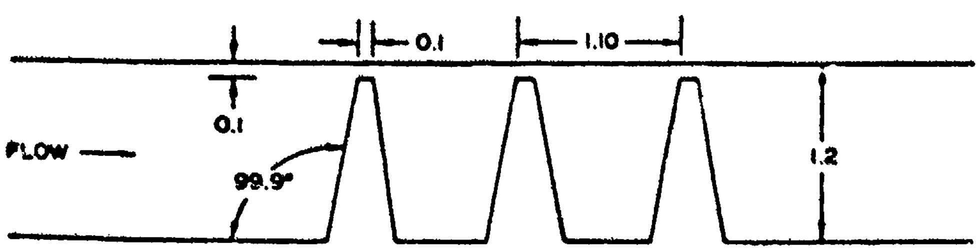
Figure 39. Stepped seal configurations tested in support of the Analysis Model development.



(e) Tapered - Single-Knife



(f) Worn - Single-Knife



(g) Tapered - Three Knives

Figure 40. Straight seal configurations tested in support of the Analysis Model development.

Table 17.

Large-scale labyrinth seal performance tests for the Analysis Model verification.*

Config Number	Scale	Rig	Seal Type	KN	KO deg	KT in.	KB deg	KH in.	KP in.	SH in.	CL in.	DTC in.	Flow Direction	Land Type	Justification
1	10X	2D	Straight	1	90	0.100	19.8	1.100			0.100			Smooth	Performance
2	10X	2D	Straight	3	90	0.100	19.8	1.100	1.100		0.100			Smooth	and
3	10X	2D	Straight	1	90	0.100	19.8	1.100	1.100		0.100			Rough	Internal
4	10X	2D	Straight	3	90	0.250	11.4	1.100	1.100		0.100			Rough	Instrumentation
5	10X	2D	Straight	1	90	0.269	16.0	1.100			0.100	KR = 0.100 in.		Smooth	
6	5X	2D	Stepped	1	50	0.225	0.0	1.400		0.600	0.100	0.690	STLD	Smooth	Performance
7	5X	2D	Stepped	1	90	0.125	0.0	1.400		0.600	0.100	0.690	STLD	Smooth	and
8	5X	2D	Stepped	3	90	0.125	0.0	1.400	1.500	0.600	0.100	0.690	STLD	Smooth	Internal
9	5X	2D	Stepped	3	90	0.125	0.0	1.400	1.500	0.600	0.100	0.690	LTSD	Smooth	Instrumentation

* Performance plots are in Appendix B, section B.1.2, p 227.

2-D rig. The leakage performance from the testing of the large-scale seals was not incorporated into the Design Model data base because of the Reynolds number influence. The measured performance for the large-scale labyrinth seals, Table 17, are collected in Appendix B, section B.1.2.

6.3.2 Flow Visualization

The complex flow structure within the large-scale labyrinth seals was visualized by means of a schlieren system because it is the only system presently suitable for the observation of high-frequency, unsteady flow. The 2-D rig lends itself to the use of a Freon doping technique to generate the required density gradients. Single and multi-location seeding points were used to observe the diverse flow field phenomena. The single pass schlieren system is shown schematically in Figure 41. The imaging was done over a horizontal knife-edge so that the flow field displays $\partial\rho/\partial y$ characteristics.

The airflow through the labyrinth seals was induced at low pressure ratios to extend the viewing lengths by minimizing the mixing rates with the Freon. Pressure drop across the seals was varied between 0.01 in. H_2O and 10 in. H_2O. Testing over this range of pressure ratios confirmed the maintenance of flow field similarity. The only differences in the flow patterns occurred in the size and rotational speeds of the vortices and the angle of the expansion fan trailing the knife tip. This qualitative flow field information assists in the understanding of local velocity and turbulence interaction and provides substantiation for the flow patterns predicted by the Analysis Model.

6.3.2.1 Analysis Model Reference Seals

Seven of the fourteen reference labyrinth seal flow fields which were analyzed by the full Navier-Stokes code were visualized with the schlieren system and recorded on video tape. Table 18 defines the geometric parameters for the nine tests which comprised this effort. In Figures 42 through 48, frames representative of these recordings are presented in photographs of each of the seal configurations tested.

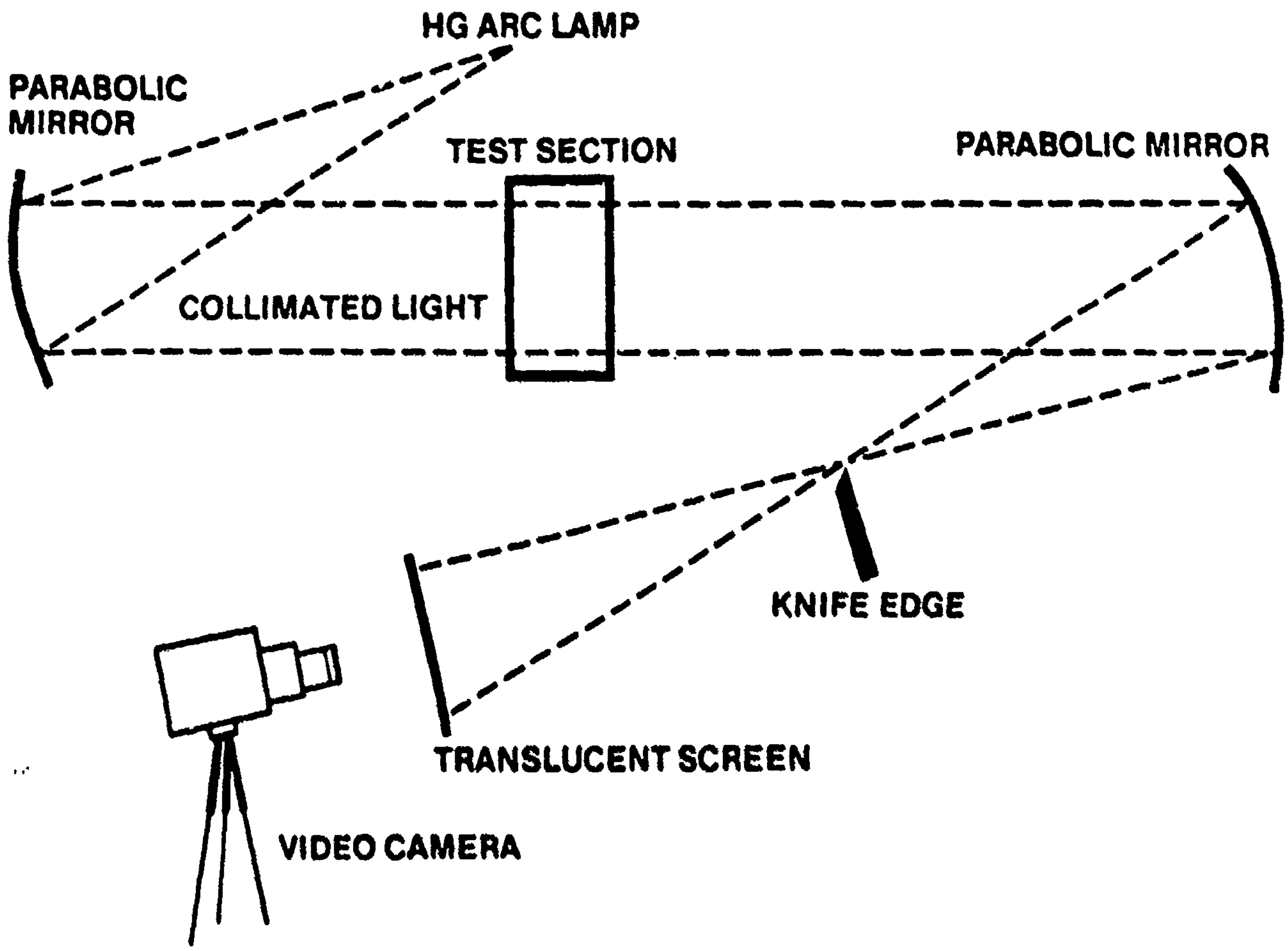


Figure 41. Schlieren imaging system.

Table 18.
Flow visualization tests for the flow field structure in the reference seals.

Objective: Observation of the flow fields in the reference straight and stepped seals (flowed in both STLD and LTSD directions) for Analysis Model development and verification.

Config Number	Scale	Rig	Seal Type	KN	Kθ deg	KT in.	Kβ deg	KH in.	KP in.	SH in.	CL in.	DTC in.	Flow Direction	Land Type	Justification
1	10X	2D	Straight	1	90	0.100	19.8	1.100			0.100			Smooth	Analysis Model
2	10X	2D	Straight	3	90	0.100	19.8	1.100	1.100		0.100			Smooth	Development and
3	10X	2D	Straight	1	90	0.169	14.0	1.100			0.100	KR = 0.100 in.		Smooth	Verification
4	5X	2D	Stepped	1	50	0.225	0.0	1.400		0.600	0.100	0.690	STLD	Smooth	
5	5X	2D	Stepped	1	90	0.125	0.0	1.400		0.600	0.100	0.690	STLD	Smooth	Analysis Model
6	5X	2D	Stepped	3	90	0.125	0.0	1.400	1.500	0.600	0.100	0.690	STLD	Smooth	Development
7	5X	2D	Stepped	3	90	0.125	15.0	1.400	1.500	0.660	0.100	0.690	STLD	Smooth	and
8	5X	2D	Stepped	3	90	0.125	0.0	1.400	1.500	0.600	0.100	0.690	LTSD	Smooth	Verification
9	5X	2D	Stepped	3	90	0.125	15.0	1.400	1.500	0.600	0.100	0.690	LTSD	Smooth	

Figure 42. Single-knife straight seal with typical sharp tip. Schlieren

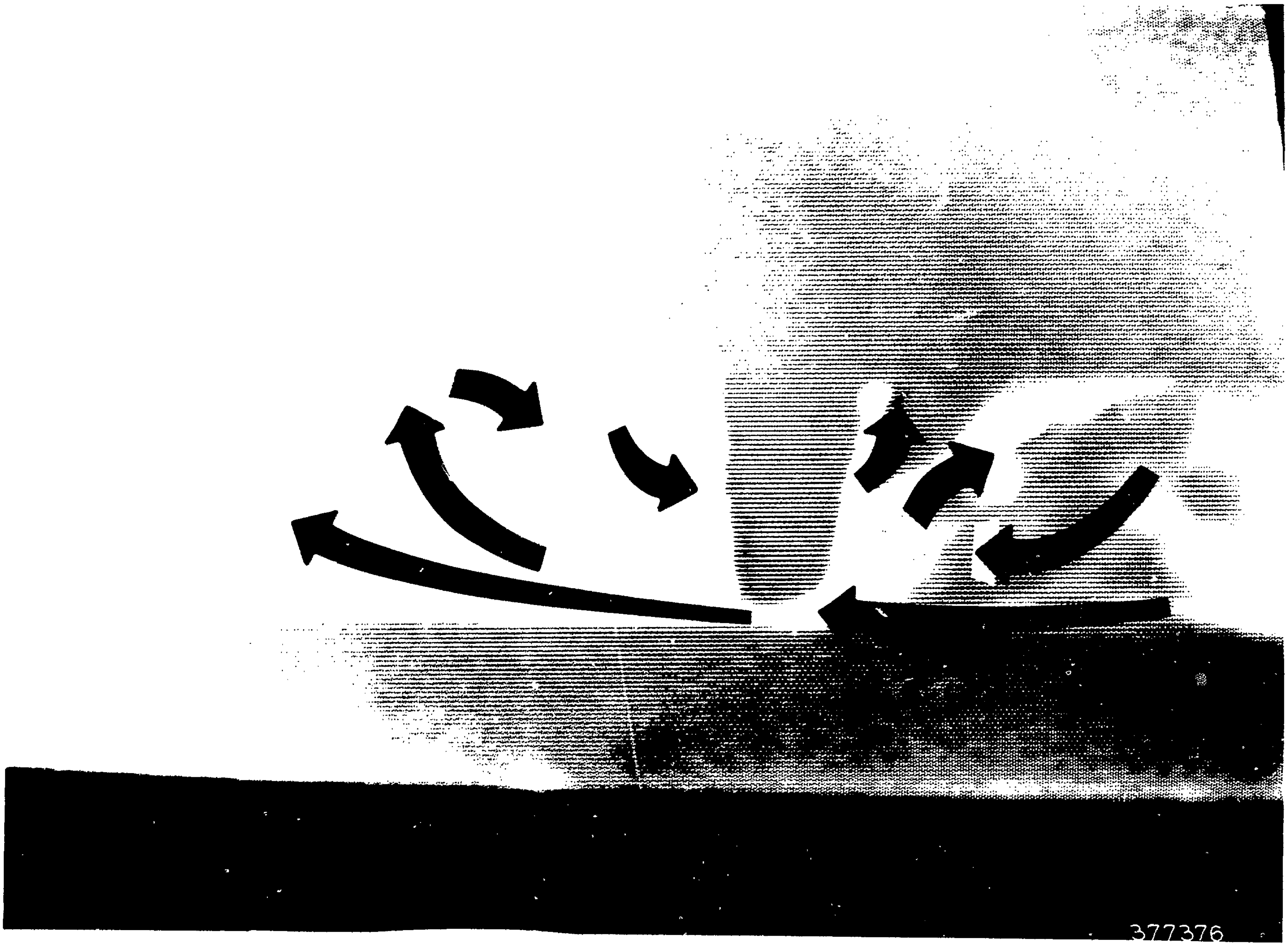


Figure 43. Single-knife straight seal with rounded tip, schlieren flow visualization at low ΔP.

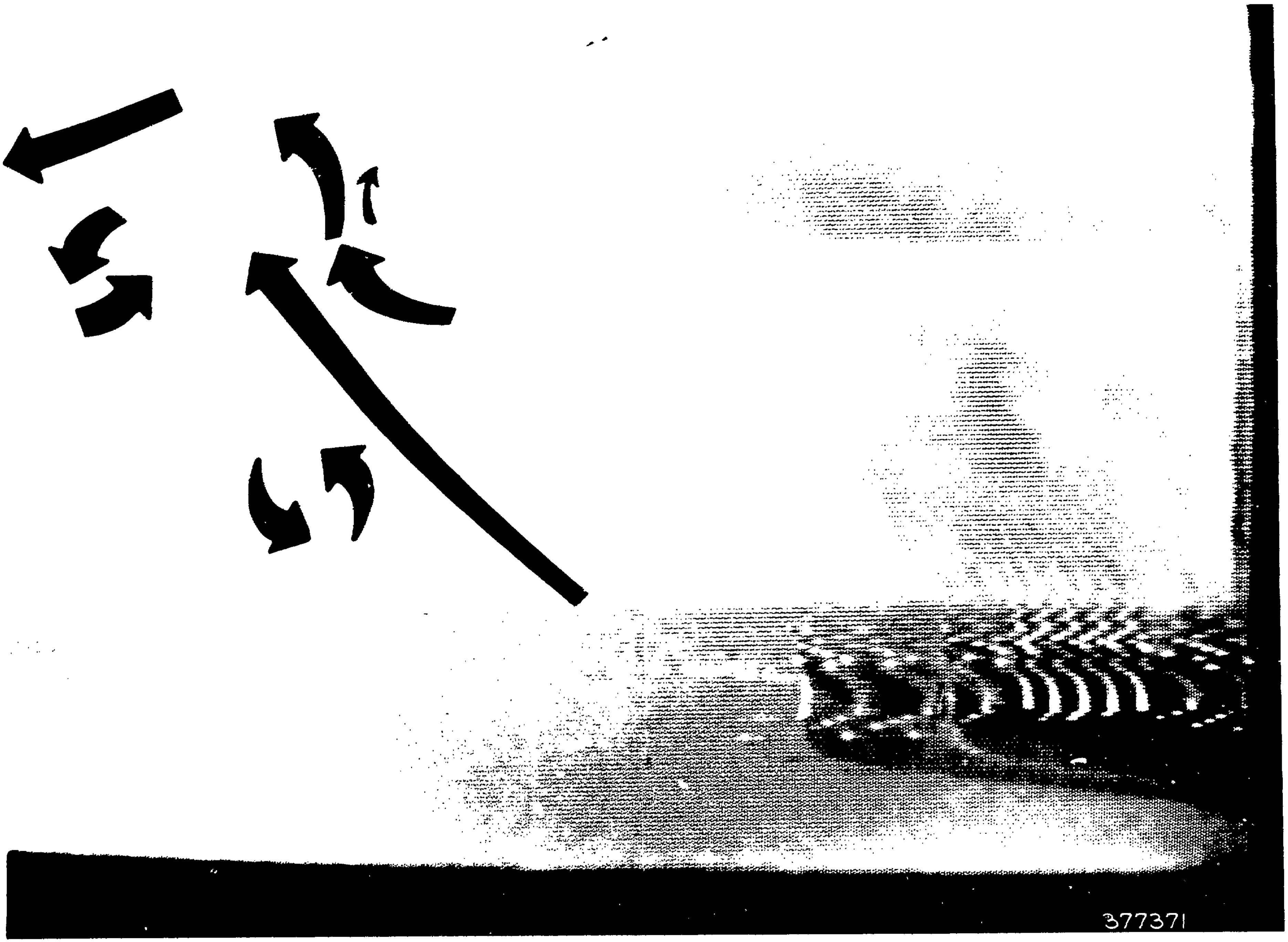


Figure 44. Single-knife stepped seal with flow in the STLD direction, schlieren flow visualization at low ΔP.

Figure 45. Single-knife slanted stepped seal with flow in the STLD direction, schlieren flow visualization at low ΔP.

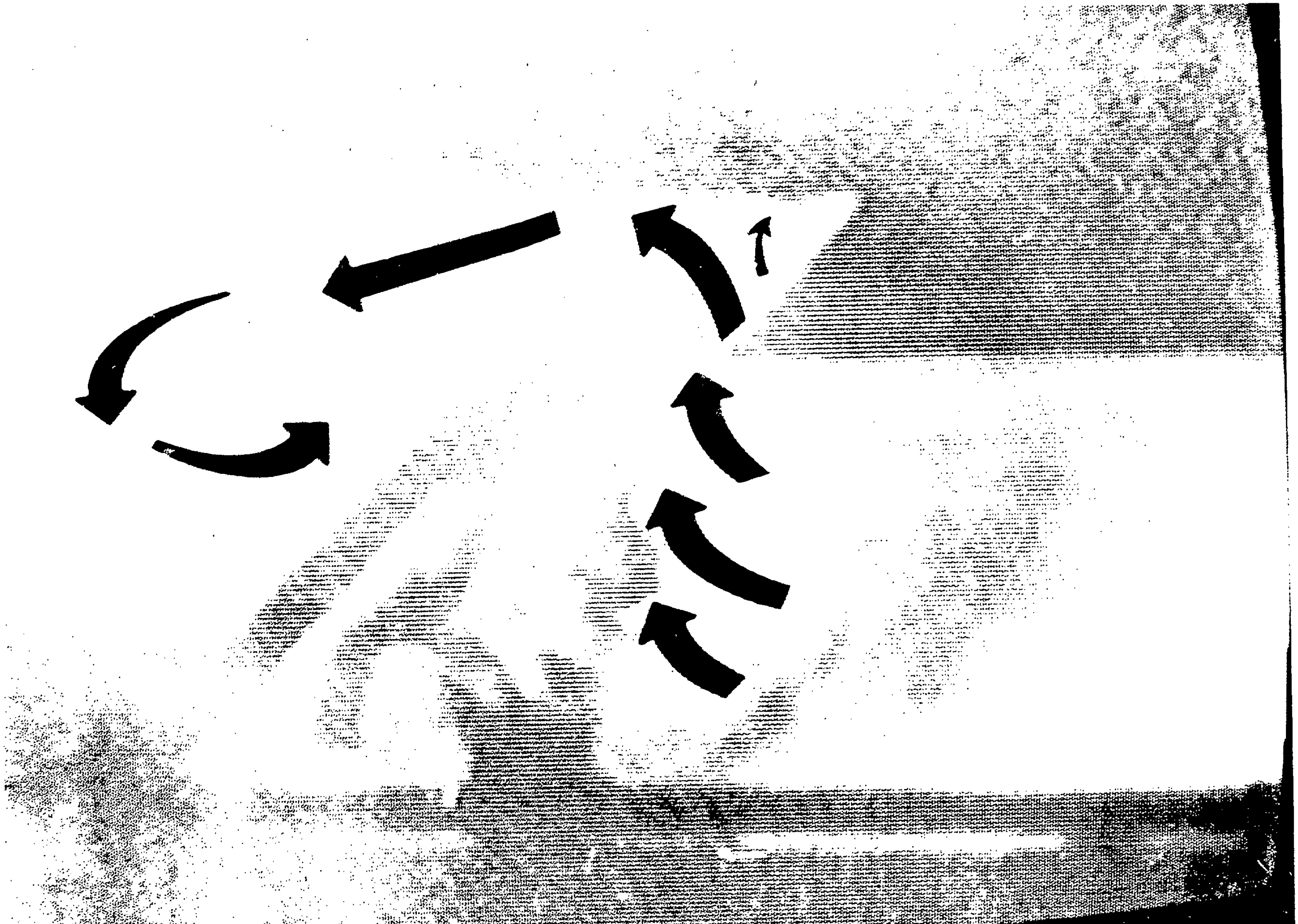


Figure 46. Three-knife straight seal, schlieren flow visualization at low ΔP.

Figure 47. Three-knife stepped seal with flow in the LTSD direction, schlieren flow visualization at low ΔP.

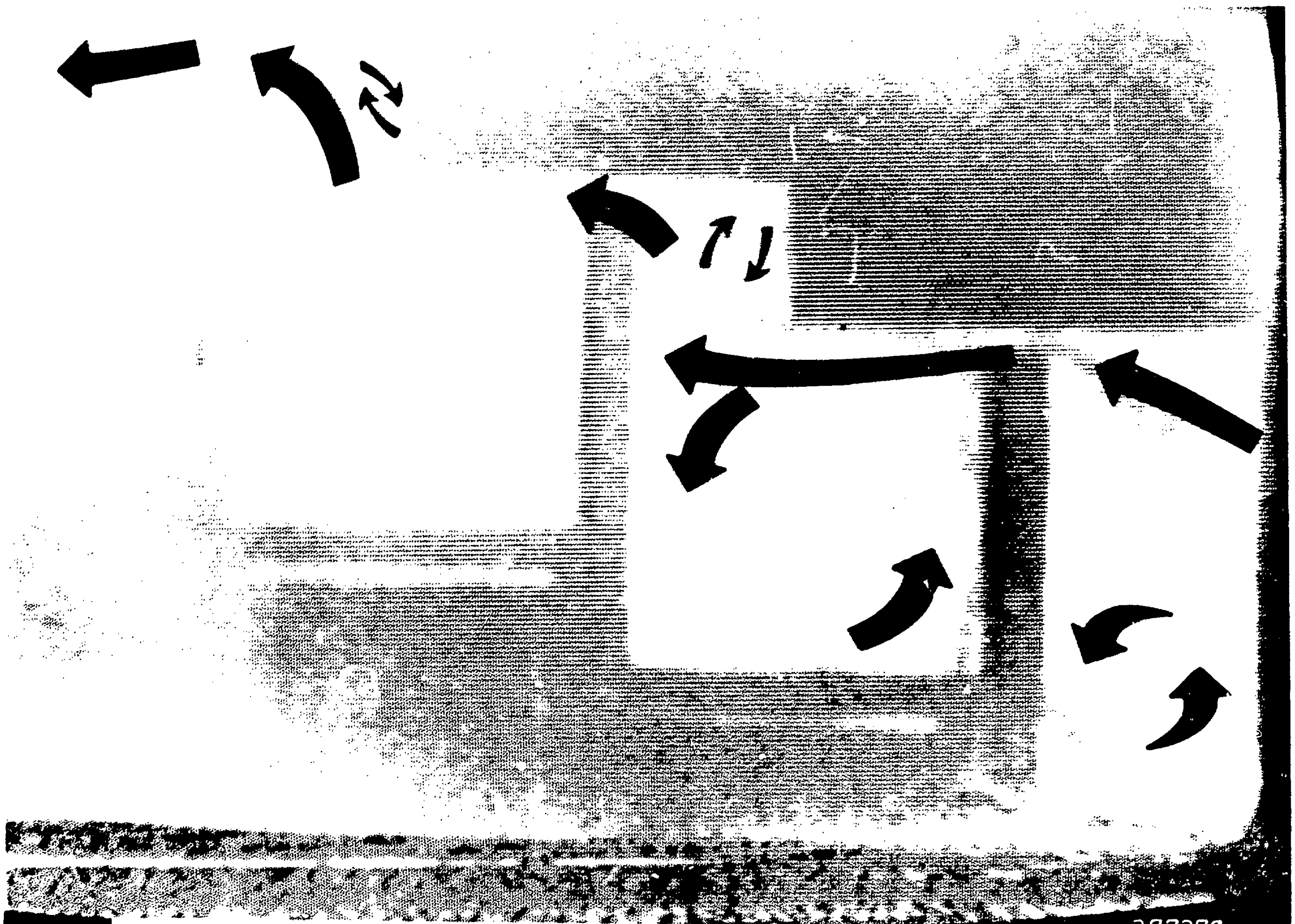


Figure 48. Three-knife stepped seal with flow in the STLD direction, Schlieren flow visualization at low ΔP

Although individual frames of the flow visualization video are not dramatically informative, flow-field characteristics associated with local velocities, separation, and stability can be readily seen from the fluid motion observed in the videotape replay on a television monitor. For example, the recording of flow over the single-knife of a straight seal, Figure 42, clearly shows the vortices upstream and downstream of the knife, as well as the acceleration and separation of the flow in the clearance gap and the diffusion angle of the discharging jet. In contrast, the flow across the knife with the rounded tip, Figure 43, shows no separation of the flow into the gap and diminished regions of vorticity both upstream and downstream from the knife. It can be seen that the presence of a backward facing step upstream from a knife creates a circuitous approach to the clearance gap which enhances the separation over the knife tip, Figure 44. The slanting of such a knife creates a re-entrant flow situation with a large well-defined vortex ahead of the knife, as visible in Figure 45, and a severe separation over the knife tip. When multiple knives are used in series, the downstream vortices are confined in the cavity much closer to the knife than would occur in the free-expansion behind a single knife. Figure 46 shows that the carry-over from upstream knives in a straight seal influences the discharge coefficients of the downstream knives by imposing a significant velocity of approach, which results from the small diffusion angle of the jets. The rotation of the second cavity vortex at about twice the angular velocity of the vortex in the first cavity was an interesting observation from the video taped records. The flow-field configuration in stepped seals of STLD design is much different from that of LTSD design. A comparison of Figure 47 with Figure 48 shows that both stepped seal types experience some carry-over. However, the STLD design demonstrates more flow blockage between knives and better vortex definition in the cavity and ahead of the knife than that which exists in the LTSD flow. These observations tend to reinforce the relative leakages measured during the performance tests on these labyrinth seals.

The tapered knife stepped seal was observed in both the LTSD and STLD configurations, Figures 49 and 50, respectively. The conventional tapered knives had minimal effect relative to the flow patterns observed in the

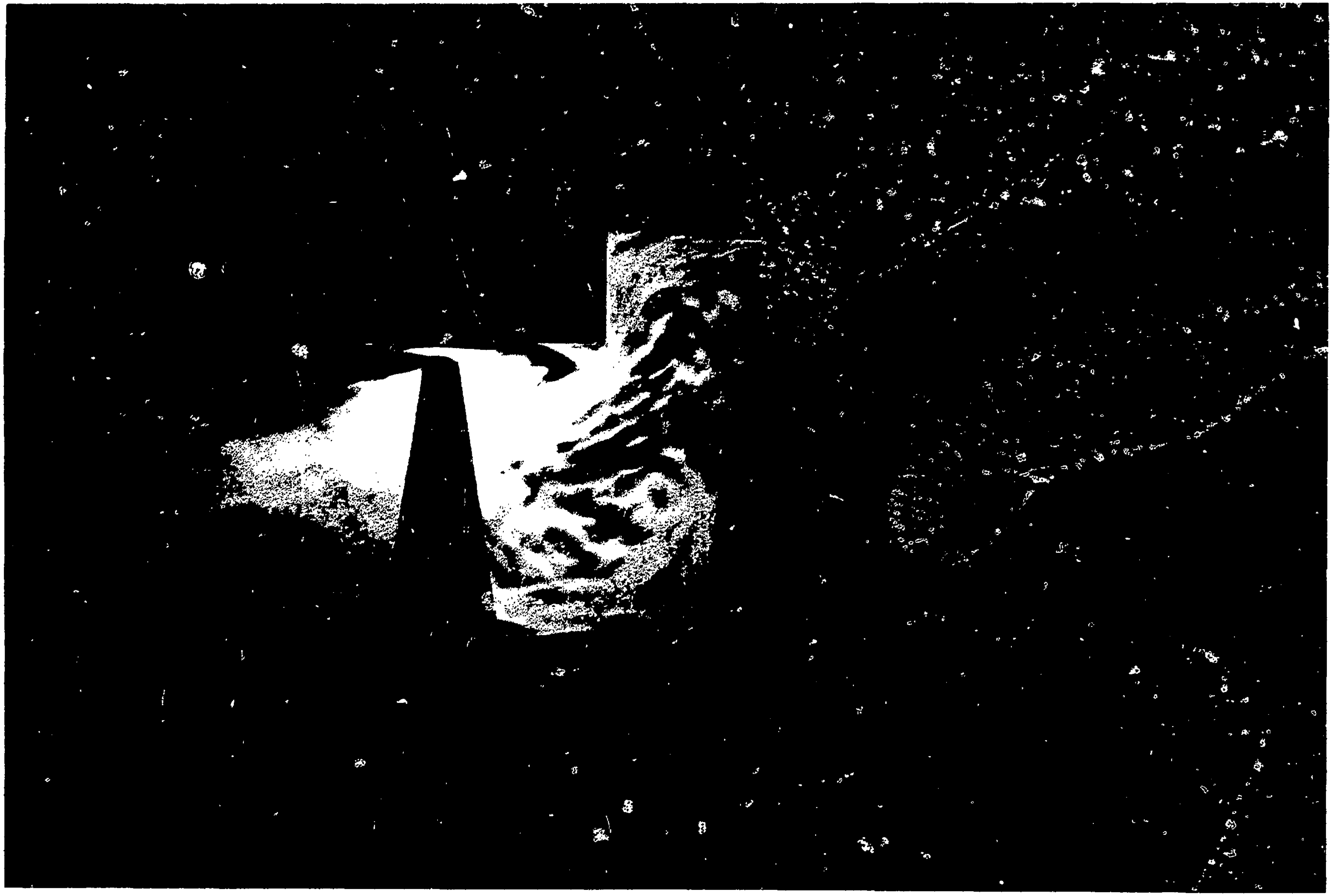


Figure 49. Tapered three-knife stepped seal with flow in the LTSD direction (flow up the step), schlieren flow visualization at low ΔP.

Figure 50. Tapered three-knife stepped seal with flow in the STLD direction (flow down the step), schlieren flow visualization at low ΔP.

similar seals with rectangular knives. For flow in the direction of small diameter to large diameter (STLD), the seal exhibits a pair of counter-rotating vortices between knives. For flow in the direction of large diameter to small diameter (LTSD), the seal maintains three vortices between knives with a nebulous transitory region in the wake of the upstream knife.

6.3.2.2 Straight Seal Parameter Effects

Another flow visualization study, Table 19, was made to investigate the effects of knife edge sharpness (KR/CL) and interknife cavity aspect ratio (KP/KH) on the seal flow field. The observations of these sixteen tests were recorded on video tape and used to rationalize the results of the performance testing on the full-scale labyrinth seal models.

Table 19.
Flow visualization tests for straight seal parameter effects.

Objective: Observation of flow field change with variable KR, KP/KH and seal clearance in 10X-scale straight seals

	Kθ	KT	KN	KH	KP	CL	Justification
1	90	0.100	3	1.10	1.10	0.050	round tip, CL
2	90	0.100	3	1.10	1.10	0.100	round tip, CL
3	90	0.100	3	1.10	1.10	0.200	round tip, CL
4	90	0.100	3	1.10	0.55	0.100	round tip, KP/KH
5	90	0.100	3	1.10	1.10	0.050	CL
6	90	0.100	3	1.10	1.10	0.100	hot-wire baseline
7	90	0.100	3	1.10	1.10	0.200	CL
8	90	0.100	3	1.10	0.55	0.050	KP/KH, CL
9	90	0.100	3	1.10	0.55	0.100	KP/KH, CL
10	90	0.100	3	1.10	0.55	0.200	KP/KH, CL
11	90	0.100	3	0.275	1.10	0.050	KP/KH, CL
12	90	0.100	3	0.275	1.10	0.100	KP/KH, CL
13	90	0.100	3	0.275	1.10	0.200	KP/KH, CL
14	90	0.100	3	0.275	0.55	0.050	KP/KH, CL
15	90	0.100	3	0.275	0.55	0.100	KP/KH, CL
16	90	0.100	3	0.275	0.55	0.200	KP/KH, CL

With the straight seal design, changing the clearance from 0.050 in. to 0.200 in. did not significantly change the observed flow patterns. The worn edged knives caused a slightly larger expansion fan than the sharp edged knives as the flow passed into the cavity between knives. Increasing the clearance decreased the relative effect of the knife tip radius (KR) based on the leakage flow passing through the clearance gap (CL). The most noticeable difference in flow patterns was observed upon changing the knife spacing (KP) relative to the knife height (KH). For KP/KH = 1.0, there is a single vortex between the knives. With KP/KH = 0.5, Figure 51, there is a double vortex between knives with the bottom vortex forming and disintegrating. With KP/KH = 2.0, Figure 52, the cavity vortex is moved downstream to the front face of the trailing knife. The backwash behind the upstream knife is nebulous and transitory.

6.3.3 Internal Pressures and Temperatures

Measurements of static pressure and total temperature were made at selected points of the intraseal flow fields of the large-scale, 2-D rig models during the performance testing. The static pressure measurements were compared with the analytical equation derived by Kearton and Keh (31):

$$\frac{P_n}{P_D} = \sqrt{\left(\frac{1}{r}\right)^2 - \frac{n}{KN}\left[\left(\frac{1}{r}\right)^2 - 1\right]} \qquad 6.1$$

where $r \geq r^*$

The total temperature measurements were evaluated against the adiabatic throttling model for seal leakage. The flow factor based on the average static pressure in the knife gap was used to calculate an effective Mach number at each knife clearance. The implied total pressure of this flow in conjunction with the measured static pressure in the downstream cavity yields an estimate for the Mach number of the carry-over. The area of the carry-over jet at the cavity static pressure taps then provides a diffusion angle for the efflux from the knife gap.

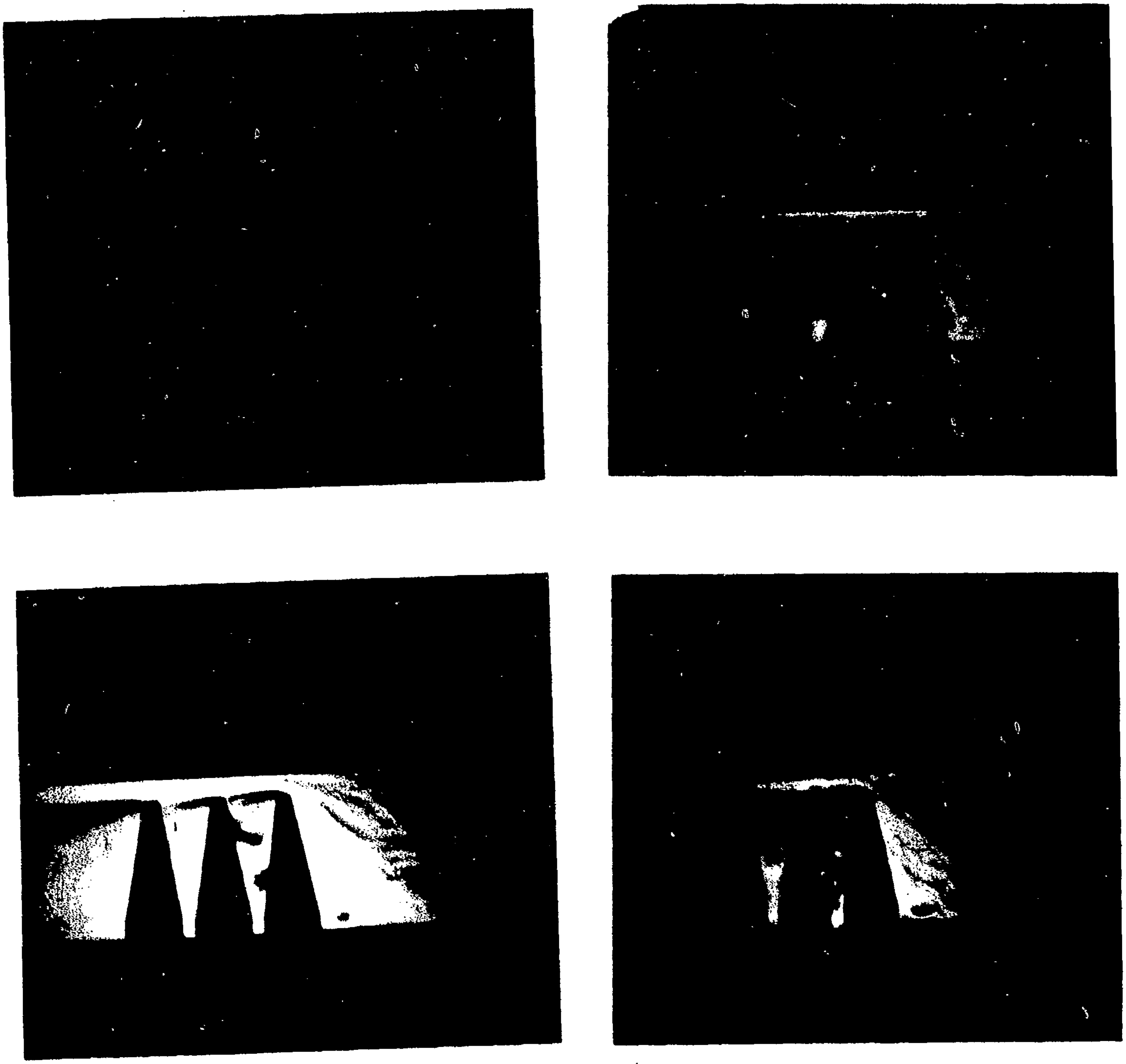


Figure 51. Vortex formation between vertical knives in a straight seal with KP/KH = 0.5.

Figure 52. Vortex formation between vertical knives in a straight seal with KP/KH = 2.0.

The typical measured pressure gradient for a straight seal is shown in Figure 53. This test was with the 10X size straight seal of three knives with a solid-smooth land. The slope increase with increasing pressure ratio is characteristic of rough lands also. A comparison with the approximate analytical equation for labyrinth seal pressure gradient derived by Kearton and Keh (Eq. 6.1) shows good agreement with the exception of the first knife which seems to provide a larger than anticipated pressure drop.

The local Mach numbers in the straight seal carry-over, as indicated by the static pressure measurements, are shown in Figure 54. As the overall pressure ratio across the seal increases, the acceleration to the last knife becomes more pronounced until choking occurs. The jet from the last knife appears to behave in the same way as the discharge from an annular, convergent nozzle with a large central base.

The total temperature measurements, as typified by Figure 55, had an unexpected characteristic apparently generated in the cavity vortices. The thermodynamic model for labyrinth seal leakage is the adiabatic throttling process. For a nearly ideal gas (air in this case), the total temperature of the system remains constant. This does not obviate the possibility of local variations in stagnation temperature which might be generated by the cavity vortices. For whatever reason, total temperature stratification occurred within the seal. The temperature in the carry-over increased as the temperature in the cavity decreased. The effect was most pronounced in the cavity behind the first knife and was intensified by increasing overall pressure ratio to approximately 2. At larger pressure ratios, no further reductions in seal cavity temperatures were observed. The phenomena were universal between smooth and rough lands and were repeatable for different model builds.

The typical measured pressure gradient for a stepped seal of LTSD design is shown in Figure 56 and of STLD design is shown in Figure 57. The superior throttling dynamics of the STLD design are indicated by the more uniform

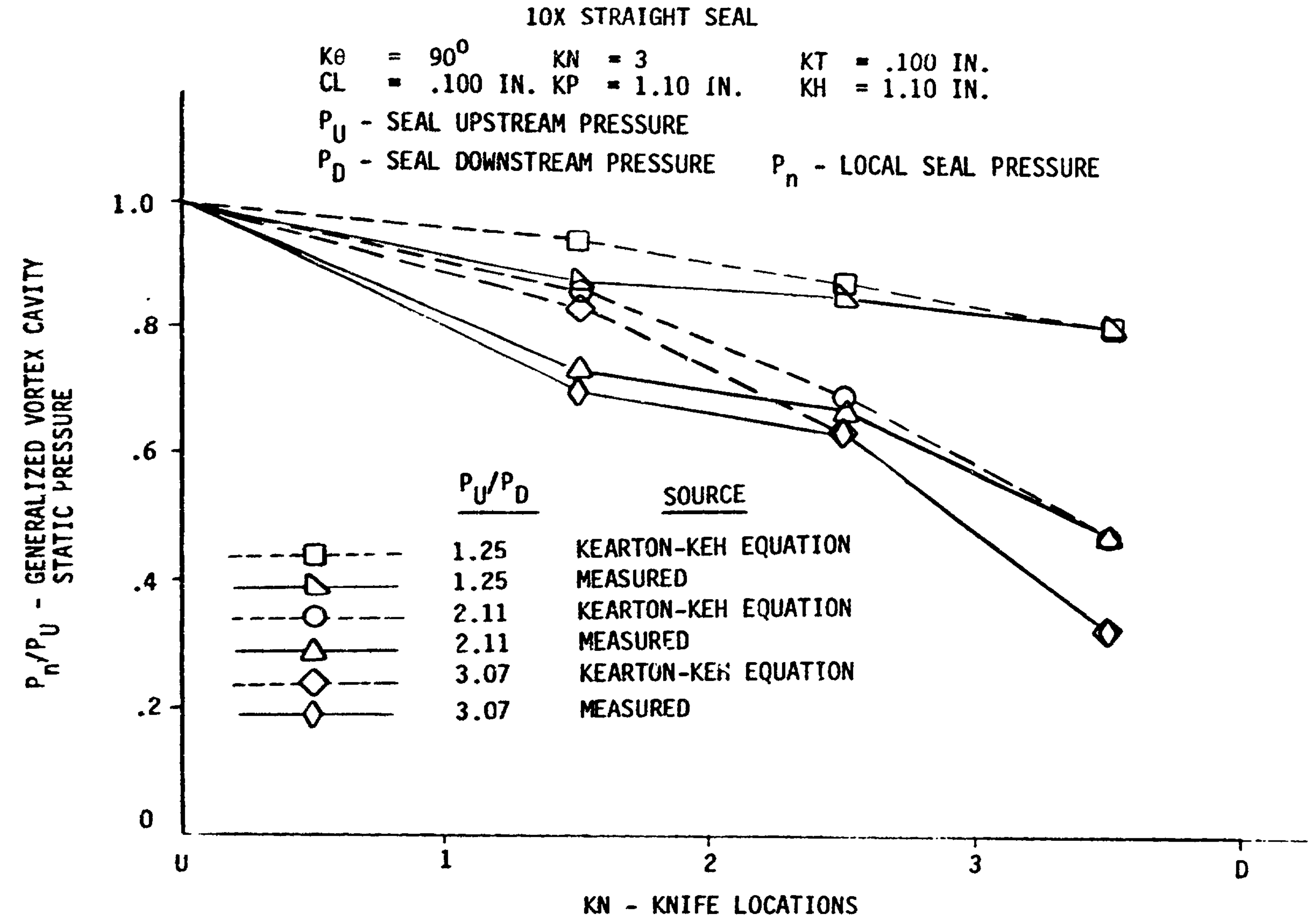


Figure 53. Pressure distribution through the large-scale three-knife straight seal.

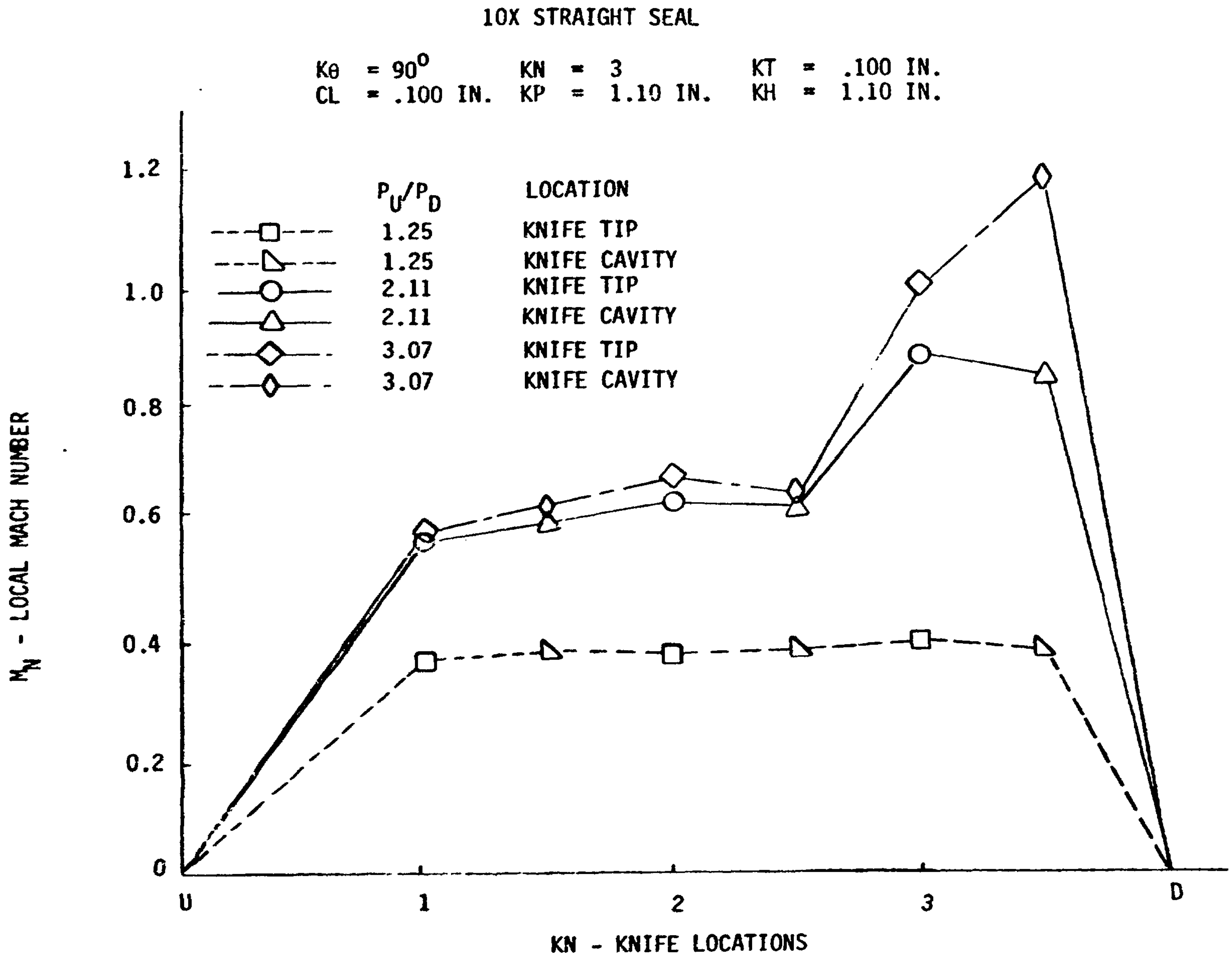


Figure 54. Mach number variation through carry-over in the large-scale three-knife straight seal.

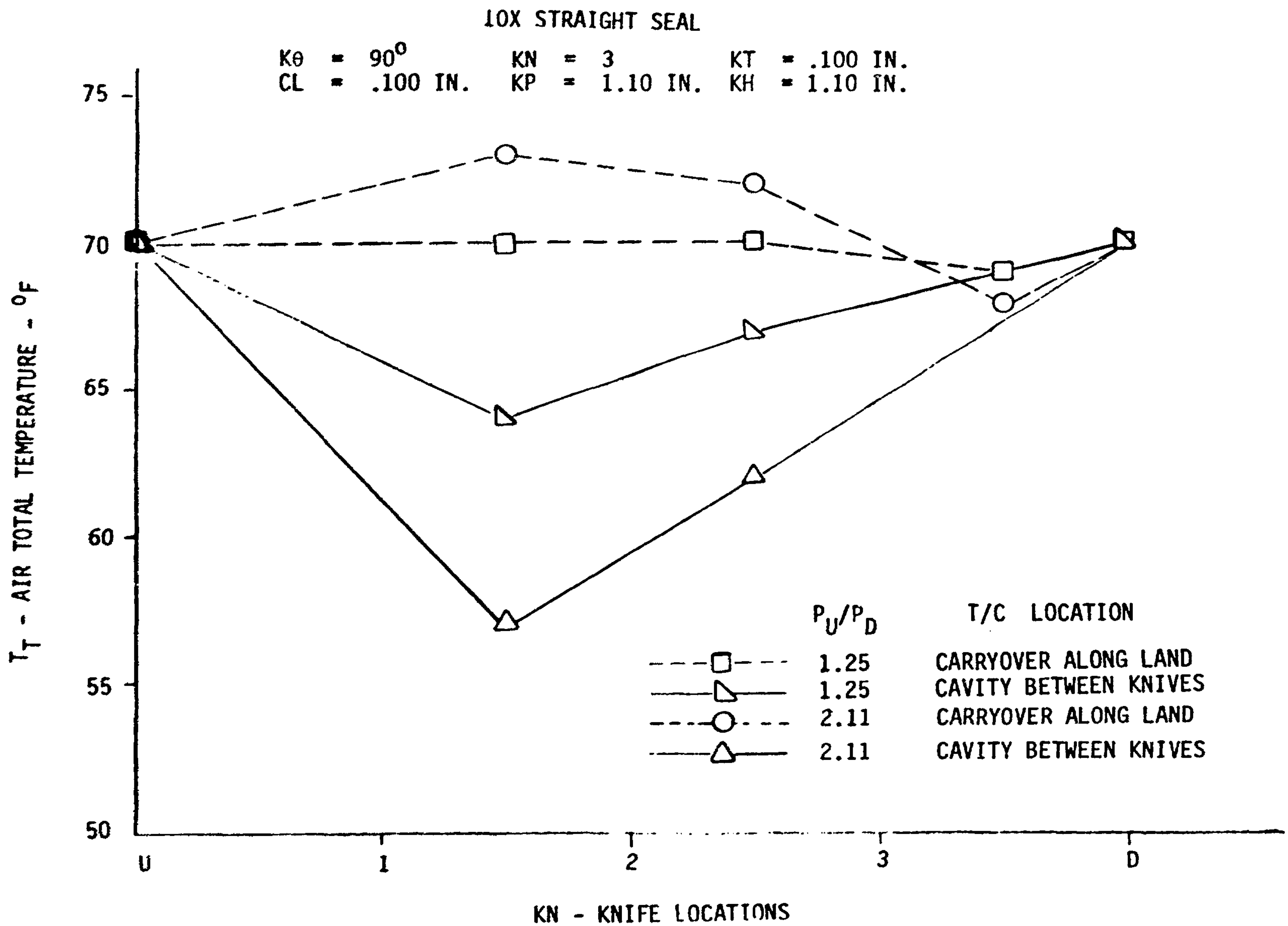


Figure 55. Internal distribution of stagnation air temperature in the large-scale three-knife straight seal.

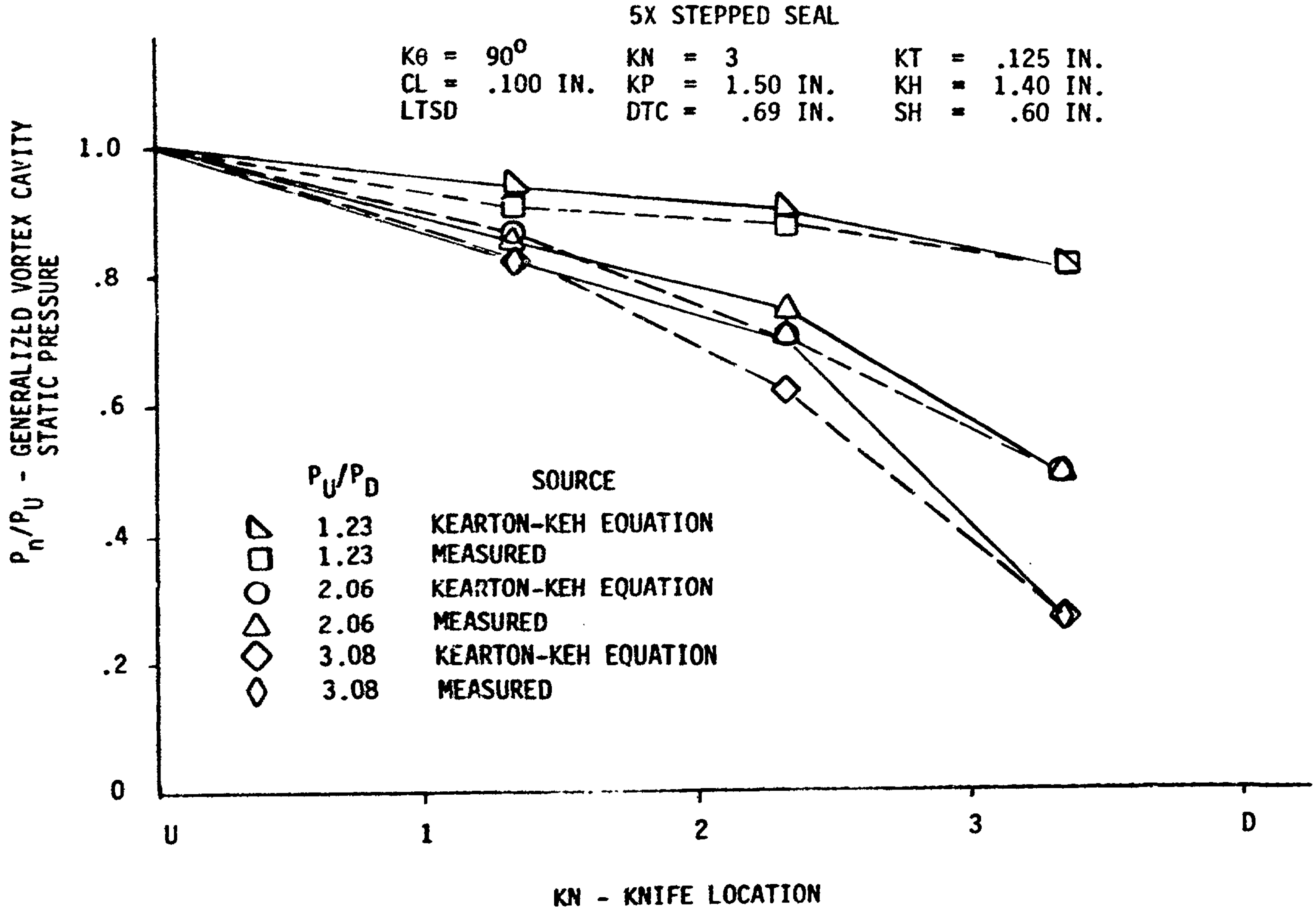


Figure 56. Pressure distribution through the large-scale three-knife LTSD stepped seal.

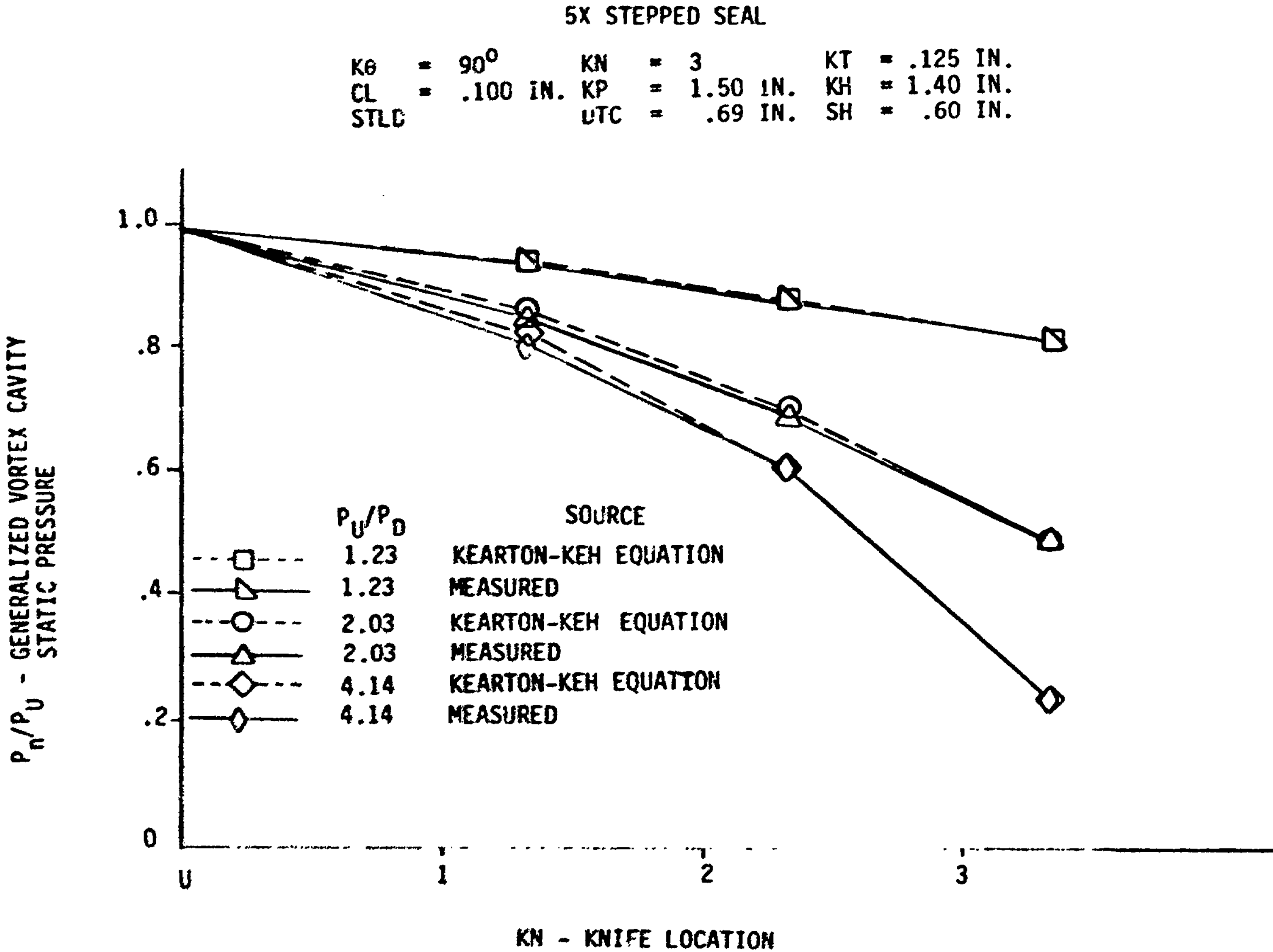


Figure 57. Pressure distribution through the large-scale three-knife STLD stepped seal.

pressure gradient to the last knife. The good correlation of the measured STLD seal pressures with the pressures predicted by the Kearton and Keh equation highlights the excellent carry-over control*.

The local Mach numbers in the stepped seal carry-over, as calculated from the static pressures, are plotted in Figure 58 for the LTSD design and in Figure 59 for the STLD design. The reduced STLD carry-over is indicated by the slightly lower Mach numbers at equivalent seal pressure ratios. Comparison with the Mach numbers of the straight seal at the same pressure ratio, Figure 54, shows that the higher leakage for the straight seal is reflected in the higher carry-over Mach number relative to both LTSD and STLD stepped seals.

Typical total temperature characteristics for the LTSD and the STLD stepped seals are illustrated by Figures 60 and 61, respectively. The temperature stratification phenomenon is identifiable in both types of stepped seals. However, the temperature distributions are observed to be different based on the measurements made in the instrumented large-scale stepped seals. The LTSD design exhibits a temperature rise at the land similar to that observed in the straight seal. However, no temperature depression was found in the between knife cavities, as was the case with the straight seal. This may be due to the serpentine "wash-through" flow characteristic seen in the cavities between LTSD knives which prevents the establishment of large, well defined cavity vortexes like those observed in the straight seals and the STLD stepped seals. However, small rotational flow fields, which form at the corners of the forward facing steps downstream of the knives and in the bottom half of the interknife cavities, must operate to produce the elevated stagnation temperatures observed at the stator land. Total temperature drops similar to but smaller than those occurring in the straight seal cavities were seen in the cavities of the STLD stepped seal. However, a combination of temperature drop followed by temperature rise occurred at the stator thermocouples in the STLD design. A satisfactory physical explanation of the total temperature measurements made in both straight and stepped seals may depend upon a more detailed Navier-Stokes analysis.

*The Kearton and Keh derivation assumes no carry-over between seal knives.

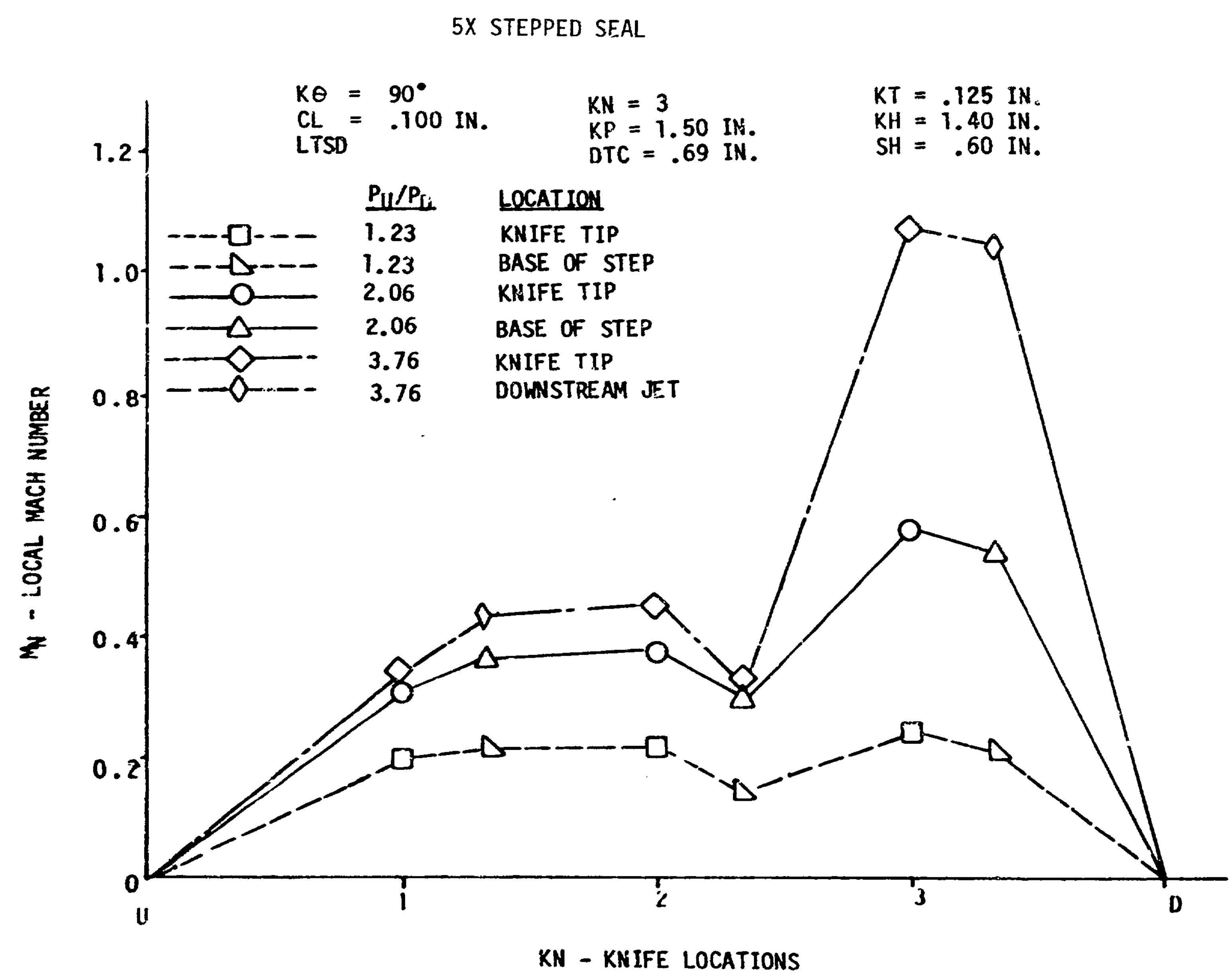


Figure 58. Mach number variation through the clearance gaps of the large-scale LTSD stepped seal.

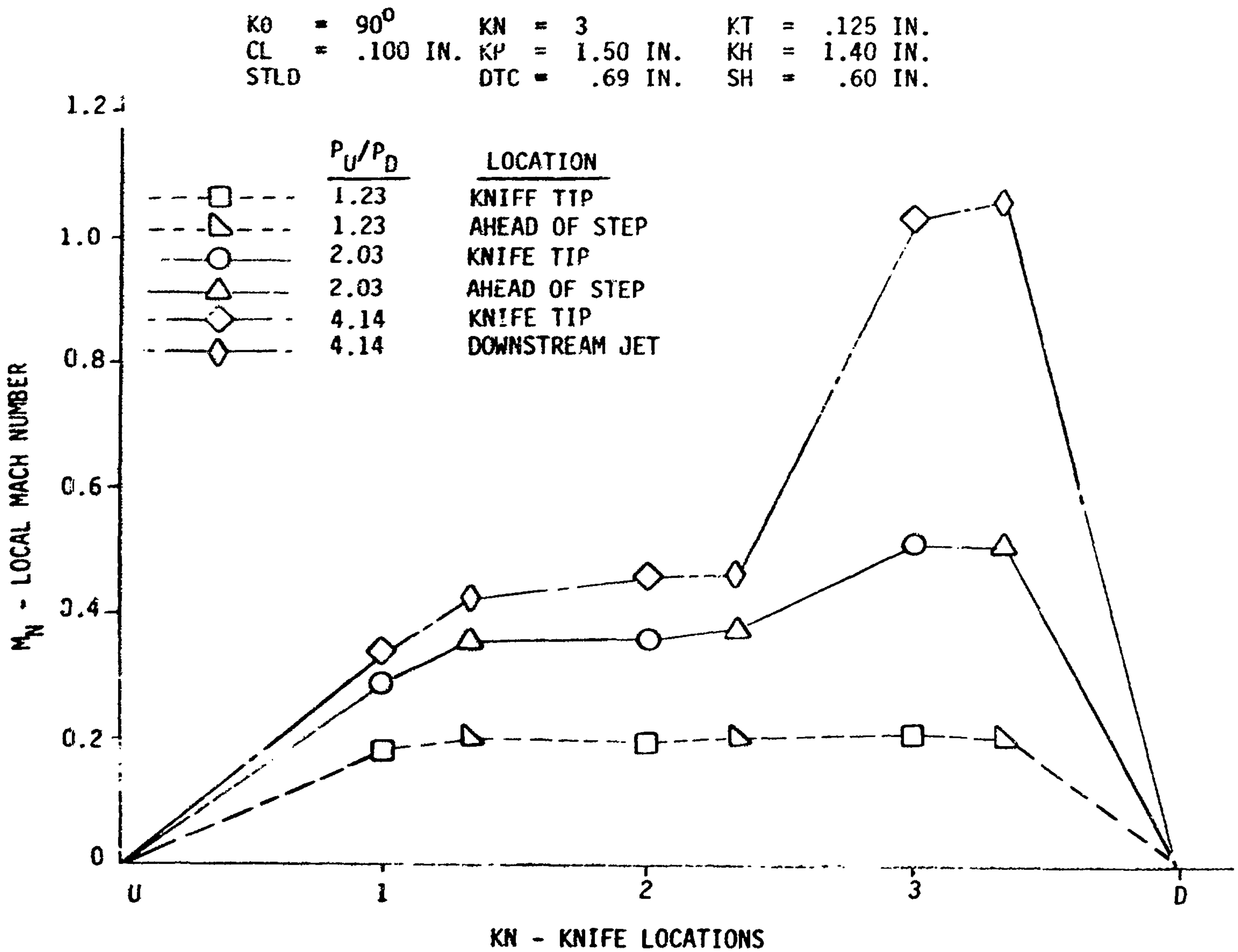


Figure 59. Mach number variation through the clearance gaps of the large-scale STLD stepped seal.

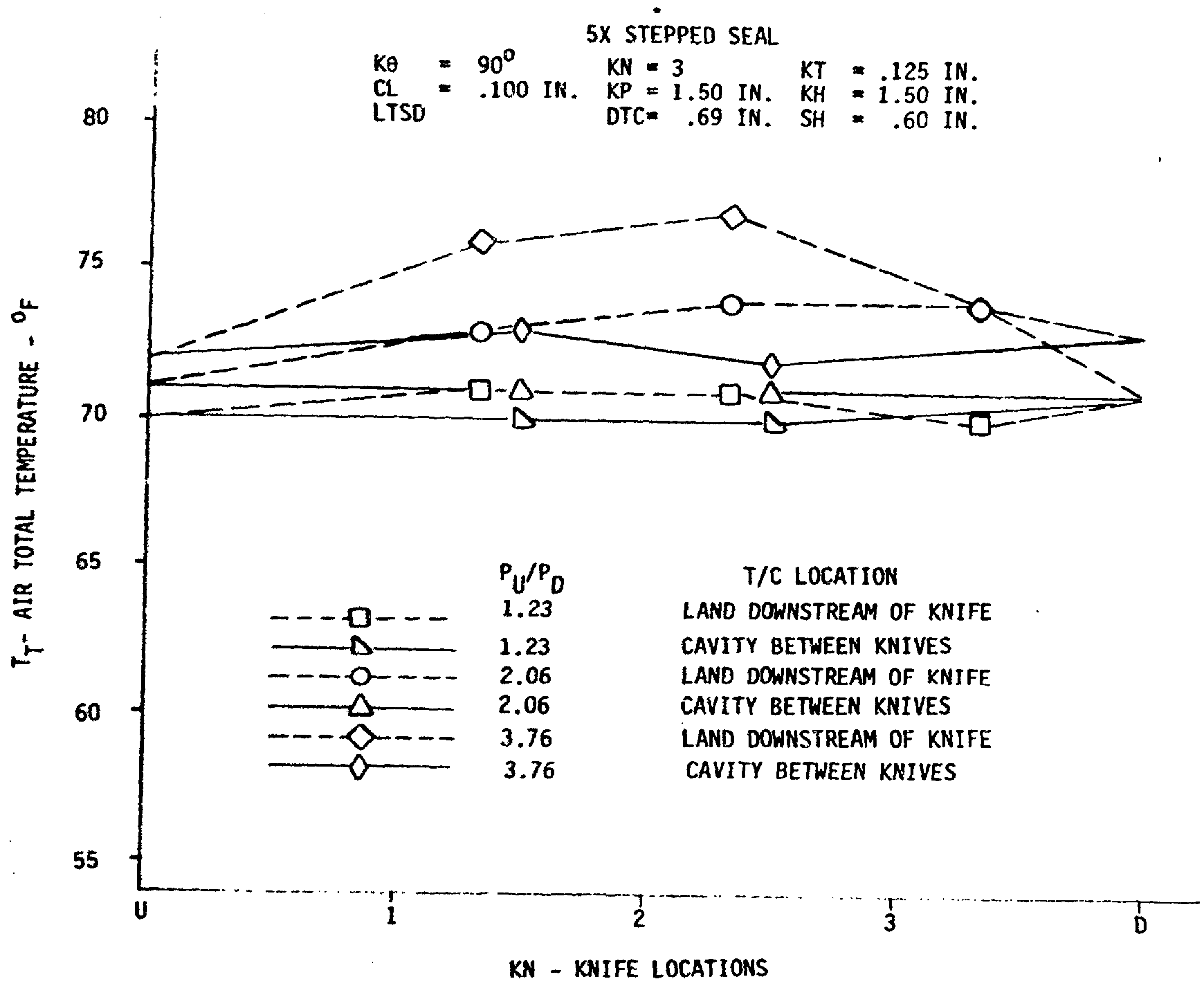


Figure 60. Internal distribution of stagnation air temperature in the large-scale LTSD stepped seal.

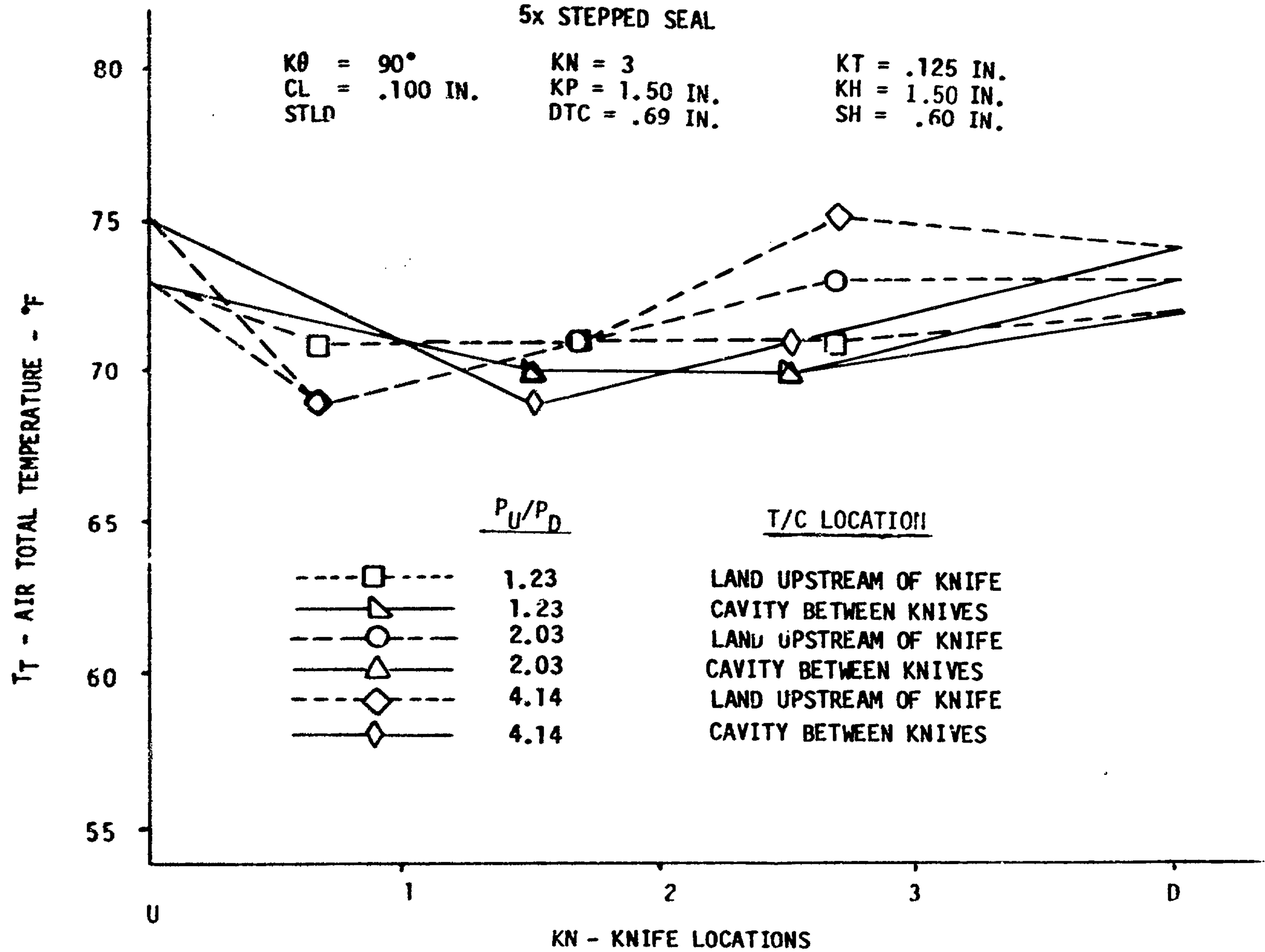


Figure 61. Internal distribution of stagnation air temperature in the large-scale STLD stepped seal.

Static pressure measurements similar to those made in the 2-D rig on the large-scale hardware were made at the stator walls of a full-scale straight seal that was tested in the 3-D dynamic rig. Only the cavity pressures were measured and compared to the Kearton and Keh model for these seals. Solid-smooth and rough land hardware were used for these tests. No intraseal temperature measurements were made with the full-scale geometry. Static pressure measurements were made along the lands of a typical four-knife straight seal at the midline of the cavities to investigate carry-over perturbations caused by stator surface roughness and by rotation. The pressure gradient through the static 3-D seal exhibits the same characteristic as it did in the large-scale 2-D seal, Figures 62 and 63. An unexpectedly large part of the overall pressure drop occurs across the first knife. This characteristic is moderated by rotational effects and to a lesser extent by surface roughness.

6.3.4 Internal Velocity Profiles

The velocity profiles within the flow fields of two baseline seal configurations were measured for Analysis Model validation. The conventional configurations of a straight seal and a stepped seal in the STLD flow direction were selected as the baselines for experimental data comparison with the full Navier-Stokes calculations from the Analysis Model (66). Figure 64 is a schematic representation of the baseline three-knife straight seal with the velocity measurement stations identified by alphabetic sentinels. Figure 65 is a similar schematic for the baseline three-knife stepped seal. These seals were large-scale models from the set that was tested with the schlieren system in the 2-D rig. The availability of the flow visualization results assisted the evaluation and interpretation of the velocity measurements.

Two techniques were employed for the measurement of the velocity profiles at the designated seal stations. A Laser Doppler Velocimeter (LDV) system was selected initially, but the small size of the seal model with respect to the sampling volume of the instrumentation forced the LDV testing to be abandoned. A hot-wire anemometer system (HWA) was substituted successfully for the LDV. The experimental procedures and data are discussed, but the comparisons with the Analysis Model calculations are presented in Ref. (66).

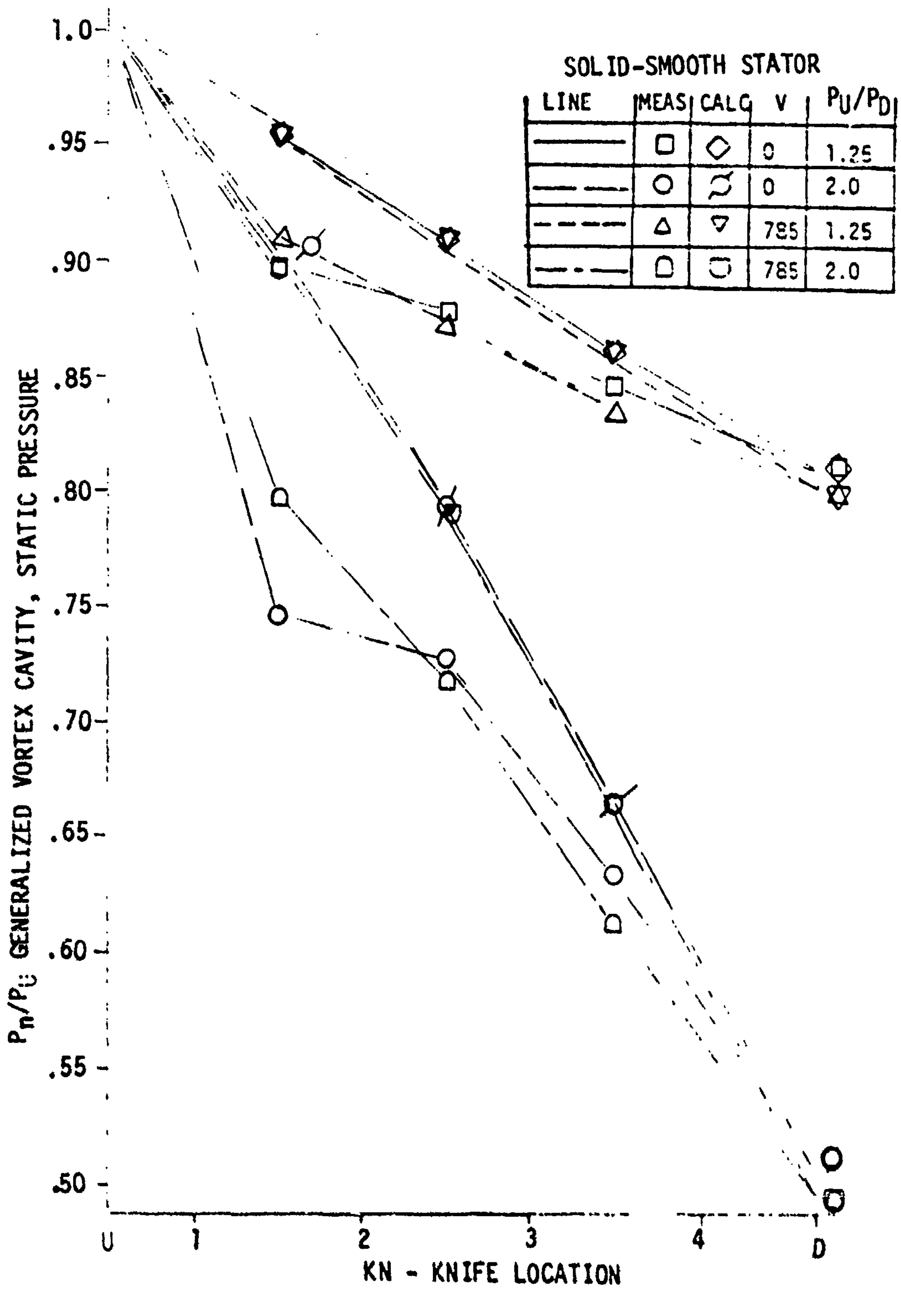


Figure 62. Static pressure drop through a straight seal with a smooth stator.

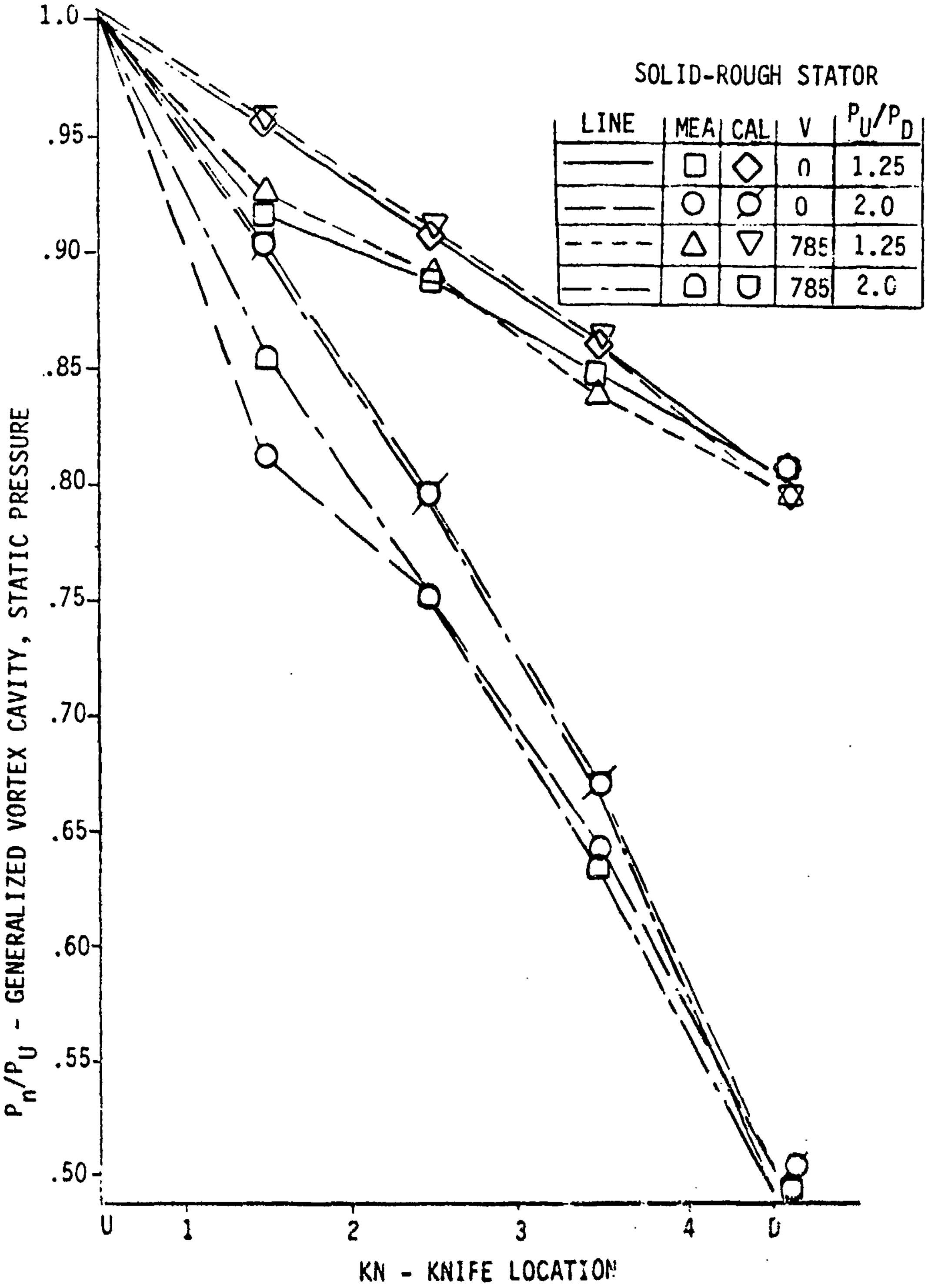


Figure 63. Static pressure drop through a straight seal with a rough stator.

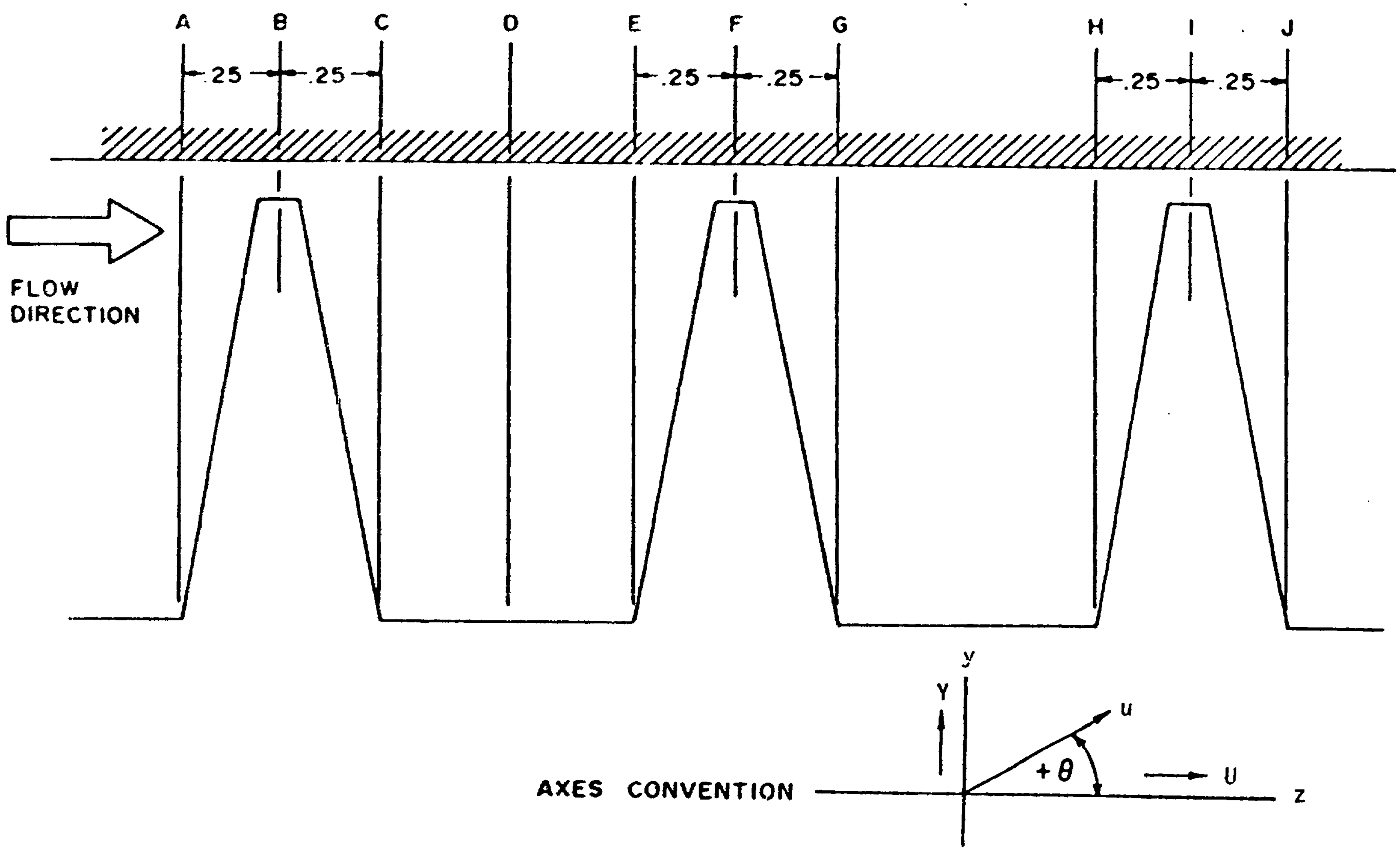


Figure 64. Data stations for the three-knife straight seal with tapered knives.

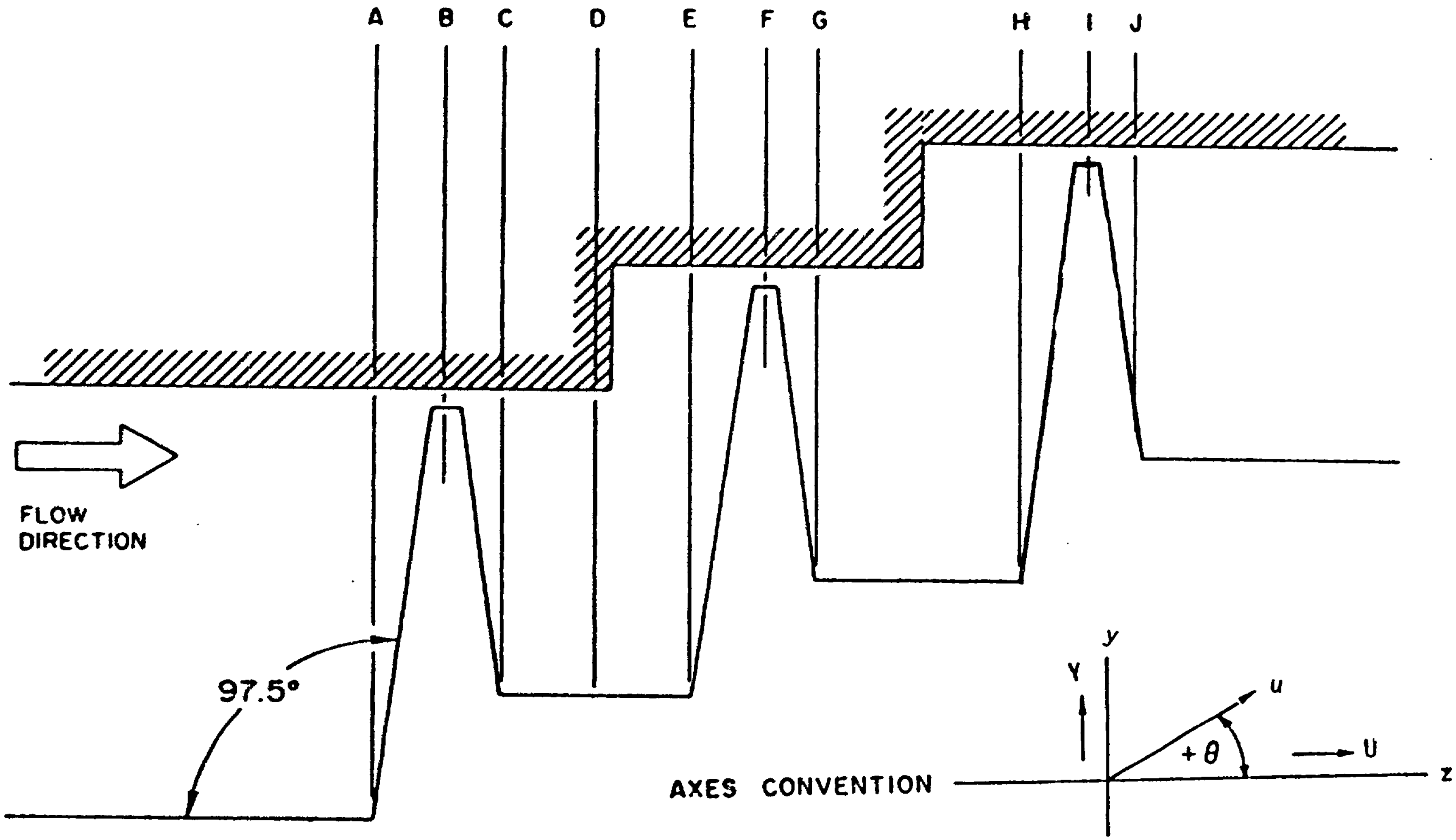


Figure 65. Data stations for the three-knife stepped seal with tapered knives.

6.3.4.1 Laser Doppler Velocimetry

The LDV technique was the instrument of choice for measuring the velocity distribution in the 2-D labyrinth seal rig models. LDV is an optical technique which does not disturb the flow and permits unambiguous determination of the flow direction. The LDV concept proposed by M. J. Rudd was utilized as shown in Figure 66. The Allison system consisted of a 4 watt Argon-ion laser for the coherent light source, a beam splitter, appropriate optics, and a photodetector to observe the frequency shift in the scattered light, which is due to the velocity of the target. The system was operated in the forward scattering mode with the laser output in the single green line. It was necessary to seed the flow with fine (1 μm average, 3 μm maximum diameter) dioctyl phthalate (DOP) oil mist to obtain sufficient reflective particulate for a measurable signal. Theoretical calculations verified that the DOP particles followed the airflow with negligible slip. A TSI processor analyzed the LDV signal.

The difficulties with the LDV system were two-fold:

1) The design and dimensions of the 2-D rig were inappropriate for the measurements being attempted.
2) The single-component LDV system was inadequate for measuring two-component velocities in the interknife cavities.

The width of the 2-D rig (6.28 in.) and the small clearance gaps (0.100 in.) of the seal models limited the laser beams to a narrow crossing angle. The resultant probe volume was on the order of 10% of the clearance gap with an aspect ratio of about 10. This relatively large probe volume tended to smear the velocity gradient toward the average velocity, especially in the neighborhood of the boundary layers. Although good correlation was obtained between the mass flowrate integrated from the velocity profile and the mass flowrate measured by a downstream orifice plate, the velocity gradients were much smaller than those predicted by the Analysis Model.

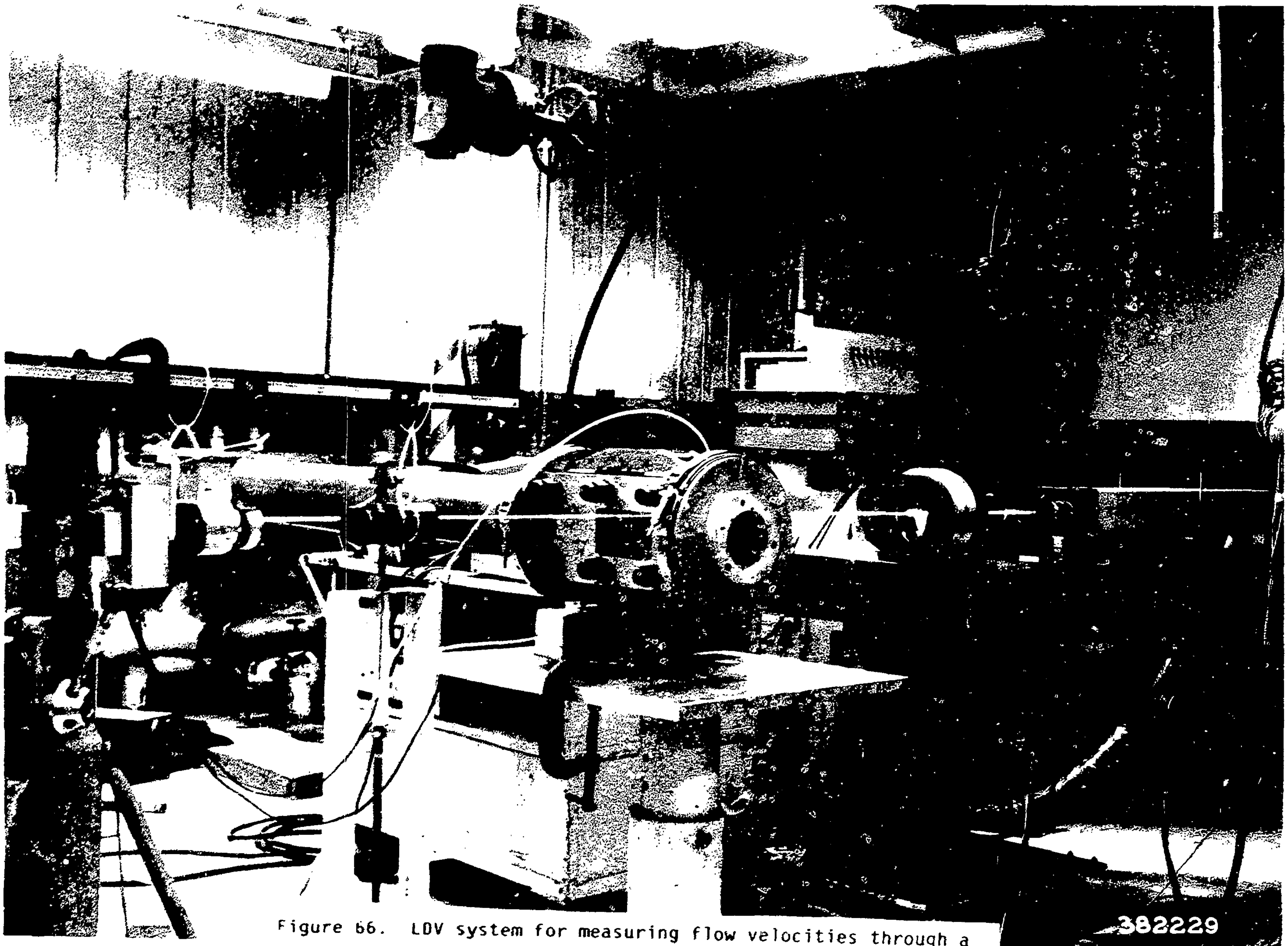


Figure 66. LDV system for measuring flow velocities through a labyrinth seal model in the 2-D test rig.

Sequential, orthogonal (at 45° and 135° to the flow in the knife gap) measurements in the interknife cavities were required of the single-component LDV system. The vortex instability made the sequential measurements for resultant velocity uncertain.

As a consequence of these experimental difficulties with the small seal model and the two-axis velocity measurements, the LDV system was abandoned in favor of hot-wire anemometer testing.

6.3.4.2 Hot-Wire Anemometry

In conjunction with the visualization of the global flow fields of the baseline seal configuration by schlieren imaging, a HWA system has sufficiently high response and accuracy to measure local velocities and turbulence intensities,

$$TI = \frac{\sqrt{\frac{\Sigma(U-\bar{U})^2}{N_p-1}}}{\frac{\Sigma U}{N_p}} \times 100\% \qquad 6.2$$

where U instantaneous velocity

$\bar{U}$ average velocity

N_p number of data samples

Since the flow visualization studies had indicated a quasi-steady, two-dimensional streamline pattern within the cavities and vortex patterns which were statistically repeatable, the HWA system can measure the local velocities in the regions of swirling, separated, or stagnated flow. The flow through the clearance gaps and in the carry-over is essentially jet-like, which makes these flows easily measured with a HWA system. The experimental arrangement of the HWA system for flow field measurements in the large-scale baseline seals in the 2-D rig is shown schematically in Figure 67.

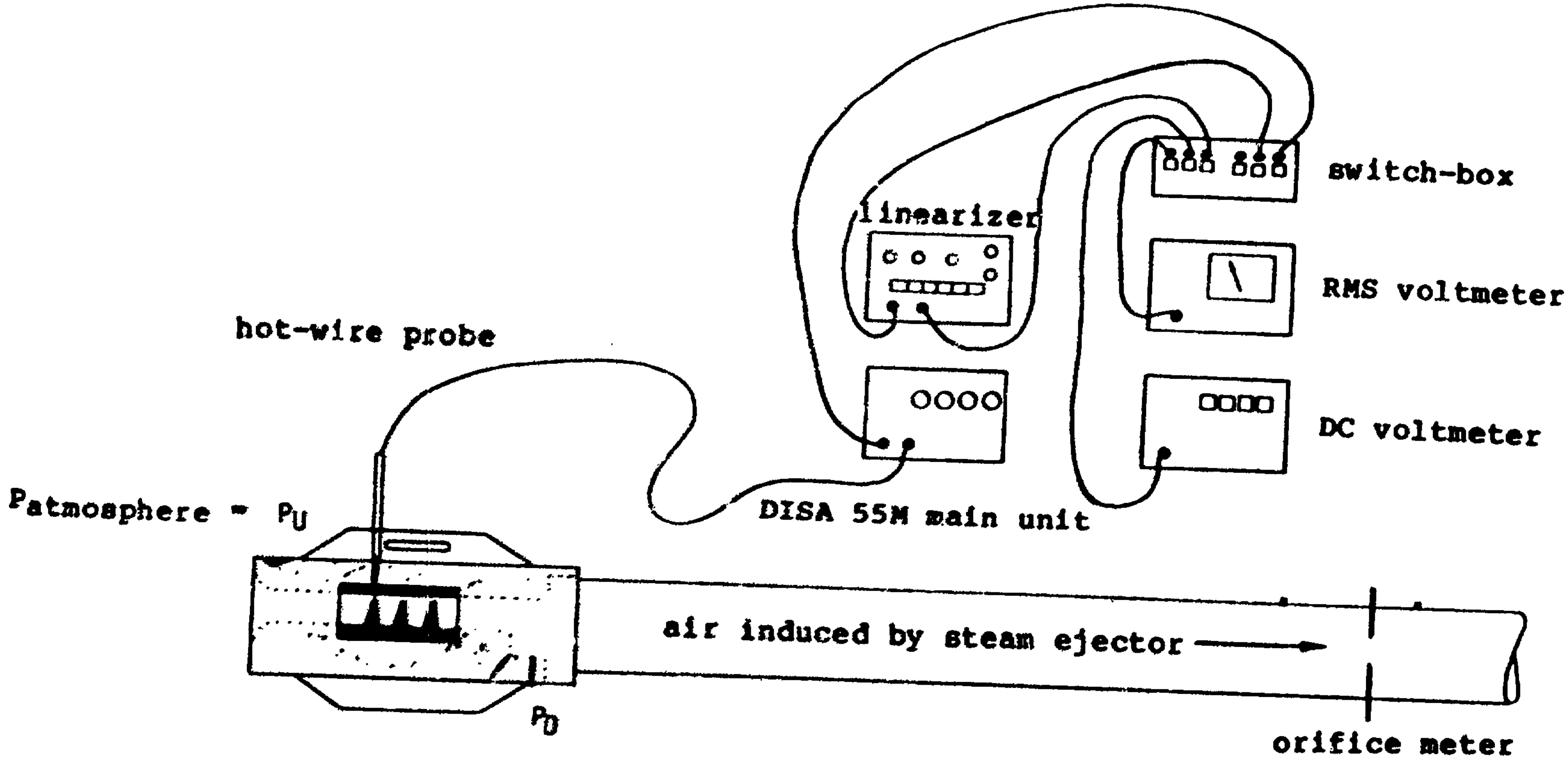


Fig. 67. Components for hot-wire anemometry measurements in the labyrinth seal model.

The DISA type 55M constant temperature anemometer (CTA) system was used for single-wire hot-wire measurements in the labyrinth seal rig. The single-wire probes used were the DISA type 55P11 straight general purpose miniature wire probes with a wire diameter of 5 μm. Calibrations of hot-wires were made using DISA calibration equipment for atmospheric pressure calibration. Subatmospheric calibrations were made using a calibrator that attached to a steam ejector which provided conditions from 12 psia to 4 psia static pressure at the hot-wire. A calibration curve was obtained for the hot-wire output voltage versus the flow velocity at conditions of constant temperature and static pressure.

The linearizer shown in the Figure 67 schematic is used to linearize the raw anemometer output voltage. The linearizer must be set up for each calibration curve over the desired measurement range. The linearized voltage and the RMS voltage are used to calculate the turbulence intensity as follows:

$$Ti = (v_{RMS}/v_{Udc})\ 100\% \qquad 6.3$$

The raw hot-wire velocity data must be corrected for density differences between the calibration conditions and the run conditions. The response of a constant-temperature hot-wire anemometer is sensitive to the product of ρU for static pressures near ambient (14.5 psia $\pm$ 4 psi). For these cases, the indicated velocity is simply corrected by a density ratio:

$$U_{TRUE} = U_{MEASURED} \times \frac{\rho_{\text{atmosph. cal.}}}{\rho_{\text{measurement cond.}}} \qquad 6.4$$

A temperature difference between calibration and run conditions requires a further hot-wire data correction, besides the temperature dependence of the density in equation 6.4.

The paper by Bearman (1971) presents a correction for ambient temperature drift to be applied to the indicated velocity. A complete correction equation to apply to hot-wire anemometer data for P_s = 14.5 psia $\pm$ 4 psi is:

$$U_{corr} = [1 + .00834(T_{meas} - T_{cal})][(P_{s\ cal}/T_{cal})/(P_{s\ meas}/T_{meas})]\ U_{meas} \qquad 6.5$$

where T is in Rankine degrees

For static pressures outside the range above, the measured velocity is determined by interpolation directly from the calibration curves, and then the multiplicative temperature correction, $[(1 + .00834\ (T_{Tmeas} - T_{Tcal})]$, is applied.

Hot-wire velocity measurements were also made at the seven measurement locations along the rig centerline shown in Figures 64 and 65. These measurements were made by inserting the hot-wire through a side plate and using a sliding clamp positioner. Flow direction was determined by minimizing the output of a single-wire hot-wire. The minimum output is reached when the hot-wire is aligned with the flow direction. A protractor attached to the hot-wire sheath gave the flow direction to an overall accuracy of ±5 deg.

Initial hot-wire anemometry work above the knives was performed by extending the hot-wire through a 0.161 in. diameter hole above the first and third knives of the straight seal. This hole was large relative to the knife tip thickness, KT = 0.100 in. The velocity profile measured above the first knife with this setup was always peaked near the knife tip. The analytical solution, on the other hand, yielded a velocity profile above the first knife that was peaked near the land and deficient near the knife tip. This velocity profile discrepancy between the analytical and experimental results above the first knife can be explained by the local diffusion into the access hole. A local reduction in the flow velocity near the land was measured by the hot-wire anemometer due to the large access hole The HWA probe tended to plug the hole as the hot-wire approached the knife tip which reduced the measurement error. However, agreement between the experimental and analytical results was obtained for the velocity profile above the third knife. The higher Mach number (.0.7) decreased the effect of the hole.

The rig hot-wire access was improved by making slotted holes to allow just the two prongs supporting the hot-wire to enter the flow field for measurements near the land. A sketch of the hot-wire access provided above the first knife is shown in Figure 68. The hot-wire was located using a precisely machined holder that was shimmed up until the sensing element was flush with the upper land. By removing shims the hot-wire was accurately extended into the flow field near the upper land.

The experience with the effect of the HWA access holes on the measurement of the labyrinth seal flow in the clearance gaps demonstrates a primary experimental difficulty with invasive instrumentation. The instrumentation distorts the parameters to be measured. Consequently hardware scale relative to all invasive components of the measuring instrument must minimize the relative disturbance to the investigated phenomena.

Discounting the perturbations of the flow field by the HWA probing system the velocity measurements had an experimental uncertainty of about $\pm 3\%$ based on instrument calibration, data interpolation, and unsteadiness.

The flow field velocities were measured at the selected locations within the stepped seal at a pressure ratio (P_U/P_D) of 2. The velocity measurements along the centerlines of the clearance gaps are given relative to the vertical distance above the knife tips in Tables 20 and 21 for the three-knife straight seal and in Table 22 for the three-knife stepped seal.

The geometry of the slots precludes the effective measurement of any small transverse velocities. Therefore, the HWA measurements in the clearance gaps consist only of streamwise velocities. The velocity measurements which were made near the faces of the knives and in the interknife cavities of the three-knife straight seal included streamwise and transverse components. The resultants of these velocities are tabulated in Table 23 for HWA measurements relative to the root of the interknife cavities. Measurements were not made along the station planes in the interknife cavities of the three-knife stepped seal.

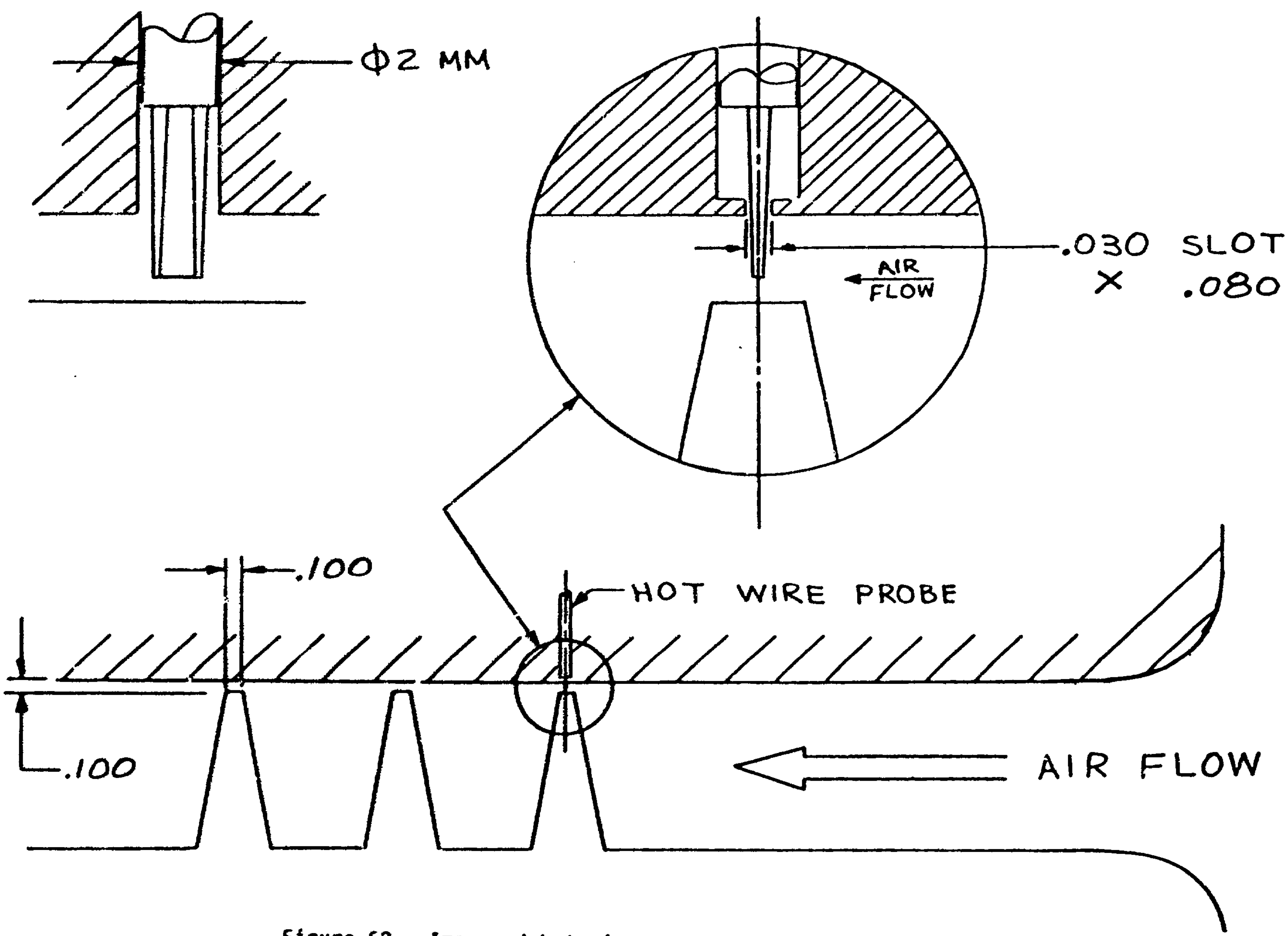


Figure 68. Improved hot-wire access to minimize flow distrubance near the land.

Table 20.
Three-knife straight (10X) labyrinth seal model
hot-wire anemometer data above the first knife at $P_R = 2.0$.

Station B

Velocity profile above the first knife, P_{static} = 11.02 psia
Test 1:

y, position in. above knife tip	U streamwise velocity, m/s	TI turbulence intensity, %
0.100	198	2.13
0.098	198	1.99
0.095	198	2.19
0.090	200	3.61
0.080	200	4.37
0.070	198	4.24
0.060	198	4.67
0.050	197	4.99
0.040	196	5.75
0.030	193	6.78
0.020	180	15.0
0.010	142	20.0
0.008	145	19.9
0.005	105	28.8

$W_{orifice}$ = 0.154 lb_m/sec
$W_{velocity\ profile}$ = 0.157 lb_m/sec (2.2% high)

Velocity profile above the first knife, P_{static} = 10.90 psia
Test 2:

y, position in. above knife tip	U streamwise velocity, m/s	TI turbulence intensity, %
0.100	197	4.73
0.097	206	2.80
0.095	206	2.91
0.090	206	3.50
0.080	205	3.68
0.070	203	3.56
0.060	202	4.01
0.050	201	3.88
0.040	198	4.84
0.030	188	7.68
0.020	172	14.6

$W_{orifice}$ = 0.154 lb_m/sec
$W_{velocity\ profile}$ = 0.156 lb_m/sec (1.7% high)

Table 21.
Three-knife straight (10X) labyrinth seal model
hot-wire anemometer data above the third knife at $P_R = 2.0$.

Station I

Velocity profile over the third knife, $P_{static} = 7.25$ psia

y, position in. above knife tip	U streamwise velocity, m/s
0.100	no measurement
0.090	285
0.080	278
0.070	270
0.060	262
0.050	255
0.040	249
0.030	243
0.020	241
0.010	226
0.005	195

$W_{orifice}$ = 0.141 lb_m/sec
$W_{velocity\ profile}$ = 0.157 lb_m/sec (11.5% high)

Table 22.
Three-knife STLD stepped (5X) labyrinth seal model
hot-wire anemometer data at $P_R = 2.0$.

Station B

Velocity profile above the first knife. $P_{static} = 12.96$ psia
$T_{total} = 70.0°F$

y, position in. above knife tip	U streamwise velocity, m/s	TI turbulence intensity, %
0.100	124	1.4
0.095	125	2.7
0.090	125	3.2
0.080	126	4.6
0.070	126	5.4
0.060	126	6.1
0.050	126	6.3
0.040	126	7.4
0.030	123	11.4
0.020	55	22
0.010	24	21

Table 22 (Con't)

Station F

Velocity profile above the second knife. P_{static} = 10.51 psia
T_{total} = 71.5°F

y, position in. above knife tip	U streamwise velocity, m/s
0.100	163
0.095	171
0.090	173
0.080	178
0.070	181
0.060	181
0.050	180
0.040	165
0.030	130
0.020	59
0.010	40

Station I

Velocity profile above the third knife. P_{static} = 7.85 psia
T_{total} = 71.5°F

y, position in. above knife tip	U streamwise velocity, m/s
0.100	no measurement
0.095	191
0.090	185
0.080	177
0.070	170
0.060	160
0.050	147
0.040	136
0.030	125
0.020	108
0:010	62

Table 23.
Velocity components in the cavity regions for the three-knife straight seal at $P_U/P_D = 2.0$.

y	STATION A u_m	STATION A θ_m	STATION C u_m	STATION C θ_m	STATION D u_m	STATION D θ_m	STATION E u_m	STATION E θ_m
1.1	49.8	28	30.4	341	74.5	0	107.5	359
1.0	42.7	39	43.1	52	50.0	14	44.3	351
0.9	33.4	50	47.9	75	30.0	4	36.7	314
0.8	26.3	56	52.5	95	20.0	14	43.1	267
0.7	19.1	55	56.3	99	17.0	90	48.8	254
0.6	13.8	47	60.9	103	17.6	90	49.6	253
0.5	10.2	25	55.1	110	20.0	128	54.5	248
0.4					34.6	160		
0.3					51.5	170		
0.2					52.8	167		
0.1					54.9	161		

y	STATION G u_m	STATION G θ_m	STATION H u_m	STATION H θ_m	STATION J u_m	STATION J θ_m
1.1	30.8	52	125.1	352	40.5	306
1.0	51.4	64	53.8	347	25.3	295
0.9	59.6	80	37.8	317	24.7	321
0.8	66.2	98	46.6	280	23.4	15
0.7	69.6	98	53.1	257	23.4	16
0.6	62.0	100	59.9	256	21.8	22
0.5	47.6	95	63.1	252	20.0	22

Legend

y (in.) - Distance from rotor
u_m(m/sec) - Measured speed
θ_m (deg) - Measured angle

The velocities measured in the straight and stepped baseline seals are compared to the calculated flow fields in Ref. (66) as a method for evaluating the computational accuracy of the Navier-Stokes solution employed in the Analysis Model. Basically the velocities measured in the clearance gaps of the three-knife straight seal were about 20% higher than those calculated. The measured velocity profiles had thinner boundary layers on both the knife tip and land than the Analysis Model results. However, the measured and predicted flow fields are qualitatively similar, especially in the cavity regions. The straight seal comparison reversed for the baseline STLD stepped seal. The measured boundary layer or separation on the knife tips was thicker than that predicted by the Analysis Model. The lack of a discernible boundary layer on the lands of either the straight seal or stepped seal models is attributed to the flow perturbation introduced by the hot-wire access slots in the lands. Qualitatively and quantitatively the comparison of the measured flow fields with the calculated flow fields was better in the stepped seal than in the straight seal.

Some of the discrepancies between experimental and analytical velocity data might be caused by the differences between the inlet velocity profiles assumed for the calculations and the inlet velocity profiles measured for the straight seal, Figure 69, and the stepped seal, Figure 70. The initial boundary layer thicknesses imposed upon the Analysis Model solutions were significantly greater than those measured at the "starting" upstream station. The carefully constructed lemniscate inlet of the 2-D rig minimized the boundary layer effect on the flow approaching the seal models. Also, the calculations did not correct for end wall losses present in the 2-D rig. There are several obvious improvements which could be made to the experimental procedures, e.g., increased model scale, non-invasive velocity measuring system, and careful simulation of far upstream and far downstream channel geometry. The Analysis Model could be modified to more accurately represent the test conditions, e.g., exact input of the measured inlet velocity profile, corrections for end wall effects, and fine tuning of the wall friction and turbulence modeling. However, as an initial attempt at numerical solutions of the full Navier-Stokes equations for the compressible flow through conventional labyrinth seals of straight and stepped configurations, the results of the Labyrinth Seal Analysis program have been very encouraging.

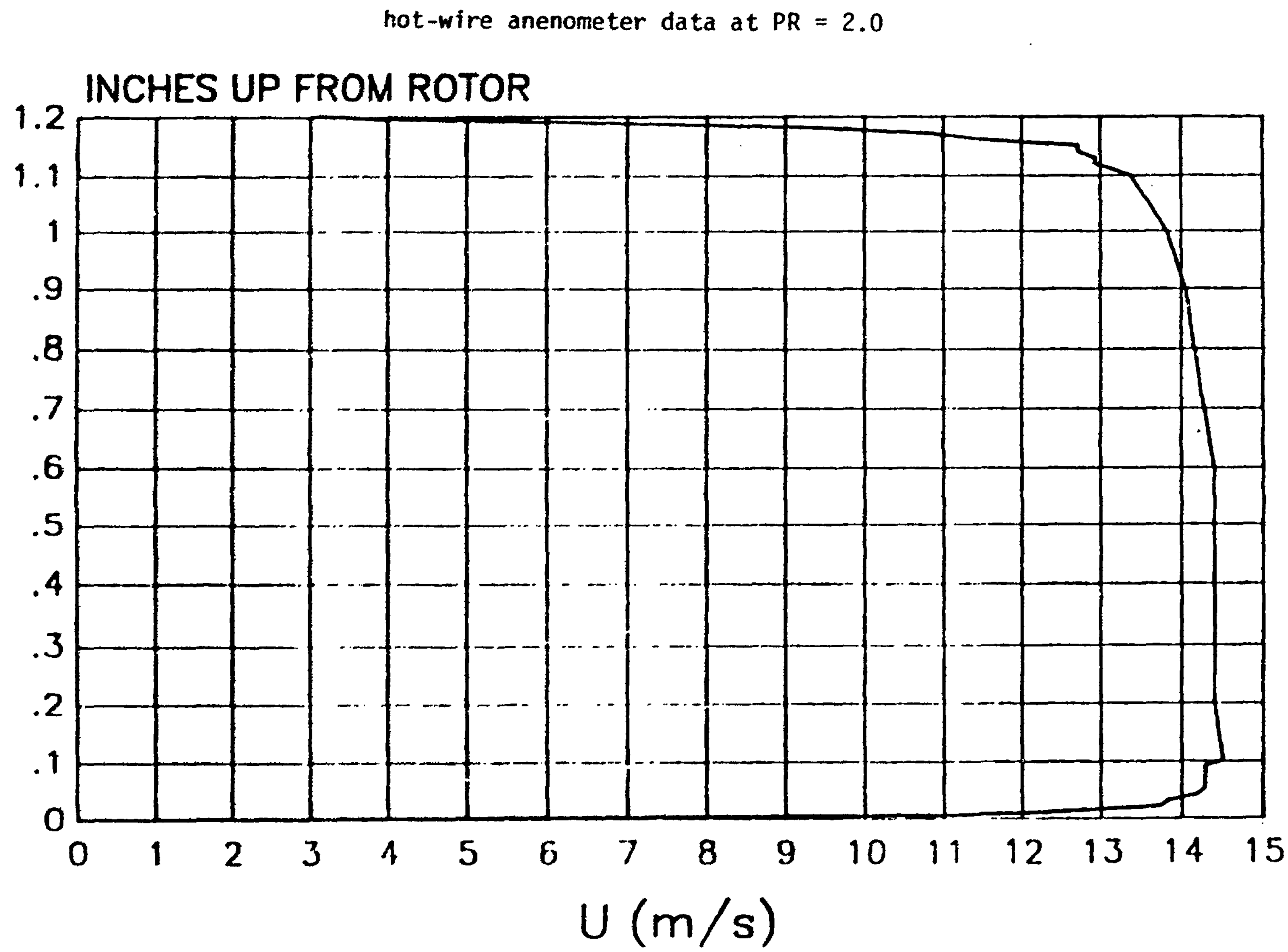


Figure 69. Measured inlet velocity profile for the three-knife straight seal.

hot-wire anemometer data at PR = 2.0

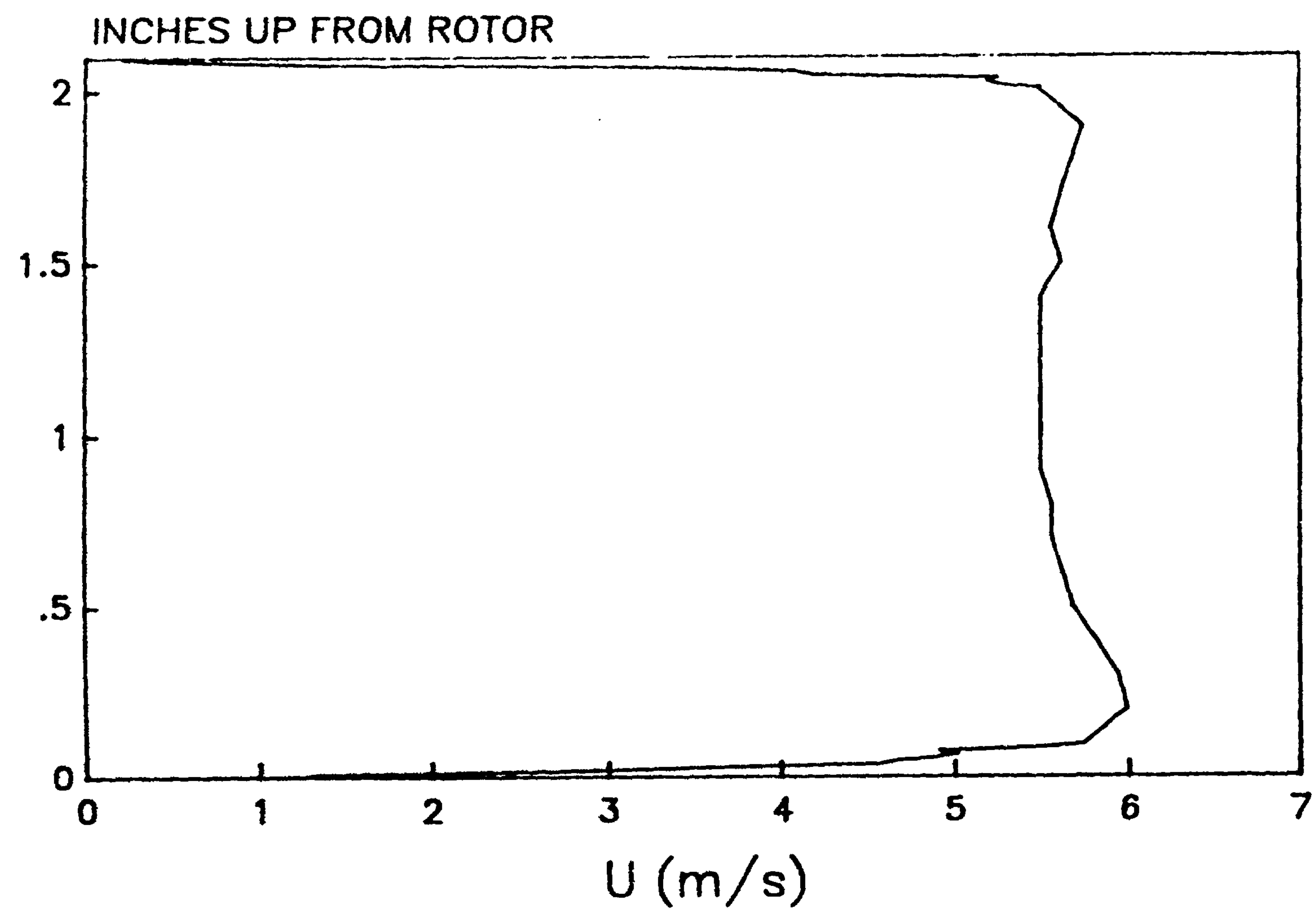


Figure 70. Measured inlet velocity profile for the three-knife STLD stepped seal.

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LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS
a	Constant	
A	Cross-sectional area	in.^{2}
A_t	Flow area between the seal knives and land, seal throat	in.^{2}
b	Thickness of land material inserts	in.
c_p	Specific heat at constant pressure	$\frac{Btu}{lb_m\ °R}$
C_D	Discharge coefficient, $C_D = w/w_{id}$	
CL	Clearance between seal knives and land	in.
DTC	Distance-to-contact: axial clearance between knife and land, undefined for constant height straight-through seals	in.
f ( )	Function of the variables ( )	
f	Fanning friction factor	
g_c	Standard gravitational acceleration mass conversion factor	$lb_m ft/lb_b se$
H	Height of the seal	in.
H	Hydraulic diameter, $H = \frac{4A}{P}$	in.
K_c	Contraction coefficient	
K_e	Expansion coefficient	
K_f	Wall friction loss coefficient	
KH	Knife height	in.
KN	Number of knives	
KP	Knife pitch	in.
KR	Knife tip radius	in.
KT	Knife tip thickness	in.
K_{vf}	Venturi-friction coefficient	
Kβ	Knife taper angle	deg. •
KΘ	Knife slant angle	deg. •
ℓ	Length of gas path	in.
ℓn	Natural or Naperian logarithm	
L	Length of the seal	in.
LTSD	Leakage flow direction from the large-to-small seal diameter	

SYMBOL	DEFINITION	UNITS
M	Mach number	
n	Specific seal knife number	
p	Land material porosity, ratio of effective open area to total area	
P	Wetted perimeter of duct	in.
P_s	Local static pressure	psia
P_D	Seal plenum downstream pressure	psia
P_n	Static pressure downstream of seal knife n	psia
P_R	Seal pressure ratio, P_U/P_D	
P_t	Local total pressure	psia
P_U	Seal plenum upstream pressure	psia
r	P_D/P_U	
r*	P_D/P_U where P_D is the maximum downstream pressure to maintain choked leakage flow through the seal	
r_k	Rotor radius at the knife tips	in.
r_t	Radius of the edge break on knife tips	in.
R	Gas constant	$\frac{lb_f\ ft}{lb_m\ {}^\circ R}$
Re	Streamwise Reynolds number, $\frac{\rho UH}{\mu}$	
Re_N	Rotational Reynolds number, $\frac{\rho\omega r_K{}^2}{\mu}$	
SH	Step height	in.
STLD	Leakage flow direction from the small-to-large seal diameter	
t	Local static temperature	°R
T	Local total temperature	°F
Ta	Taylor number, $Ta = \rho V(CL)\sqrt{\frac{CL}{r_K}} / \mu$	
T_U	Seal upstream plenum temperature	°R
u	Absolute (resultant) flow velocity at angle θ	m/sec
U	Streamwise velocity	m/sec
v	Voltage	volts
V	Seal knife tip speed	ft/sec

SYMBOL	DEFINITION	UNITS
w	Seal airflow rate	lb_m/sec
w_{id}	Ideal or isentropic airflow rate	lb_m/sec
x	Multiplication operator	
X	Honeycomb cell size	in.
XMUL	Area correction factor for clearance above a knife which is downstream of a step	
y	Vertical axis or transverse flow direction	
z	Horizontal axis or streamwise flow direction	
Z	Compressibility factor relative to a thermally perfect gas	
α	jet expansion angle	deg, °
γ	Ratio of specific heats	
Γ	Velocity carry-over factor	
δ	jet expansion height	in.
ϵ	Land surface roughness	μ in.
μ	Fluid dynamic viscosity	$\frac{lb_m}{ft\ sec}$
π	Conventional transcendental number, ratio of circular circumference to diameter	
ρ	Density	$\frac{lb_m}{ft^3}$
$\phi = \frac{w\sqrt{T_U}}{P_U A_t}$	Airflow parameter	$\frac{lb_m \cdot R^{1/2}}{lb_f\ sec}$
ω	Rotational speed, angular velocity	$\frac{rad}{sec}$

APPENDIX A

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TOTAL NUMBER OF REFERENCES FOR SEAL DYNAMICS = 52

APPENDIX B

SUPPORTING DATA FOR MODEL DEVELOPMENT

B.1 2-D RIG DATA

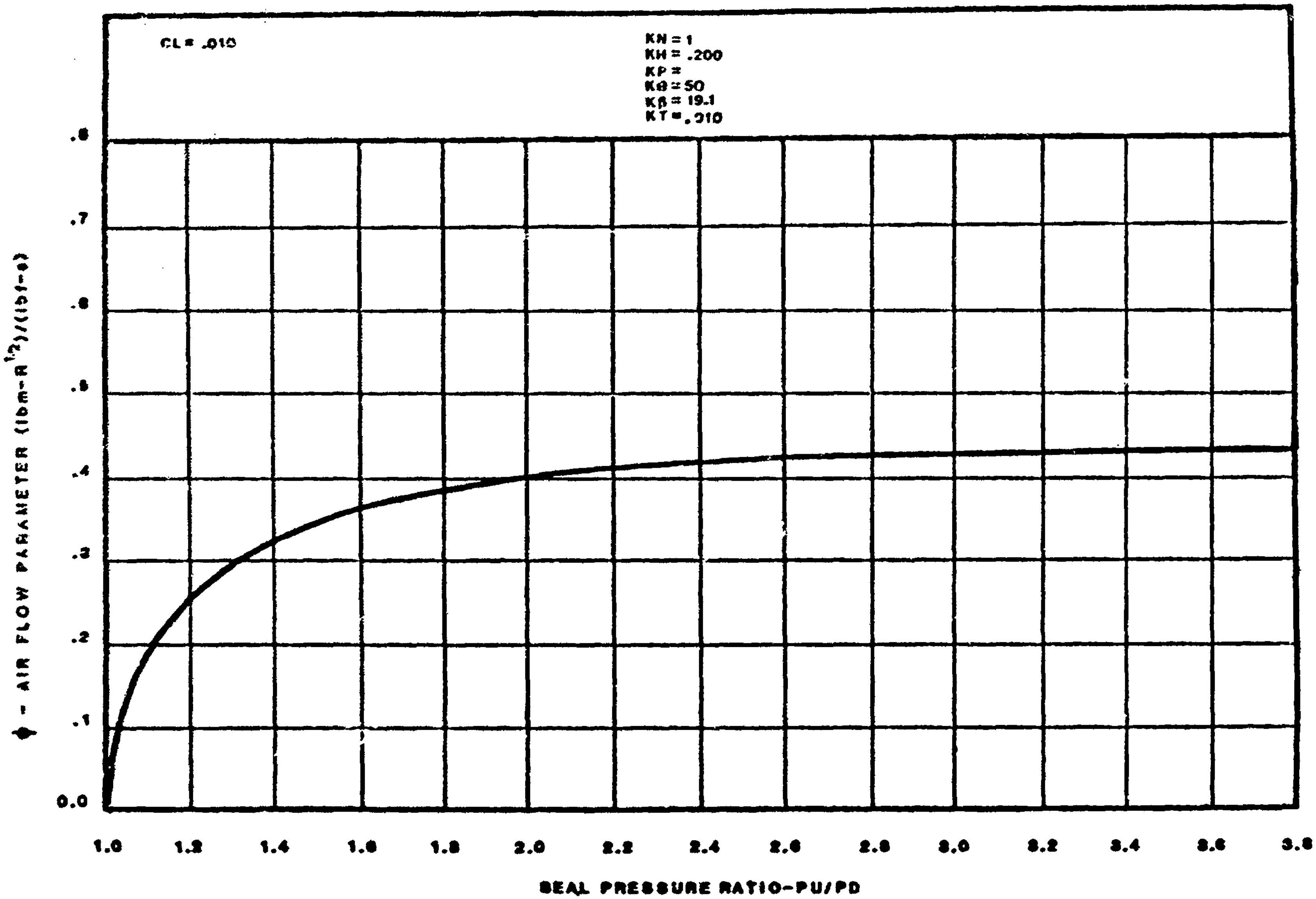
The following static data were acquired in the 2-D labyrinth seal test rig with a pressurized inlet plenum and an atmospheric exhaust. The inlet air temperatures were those of the ambient air.

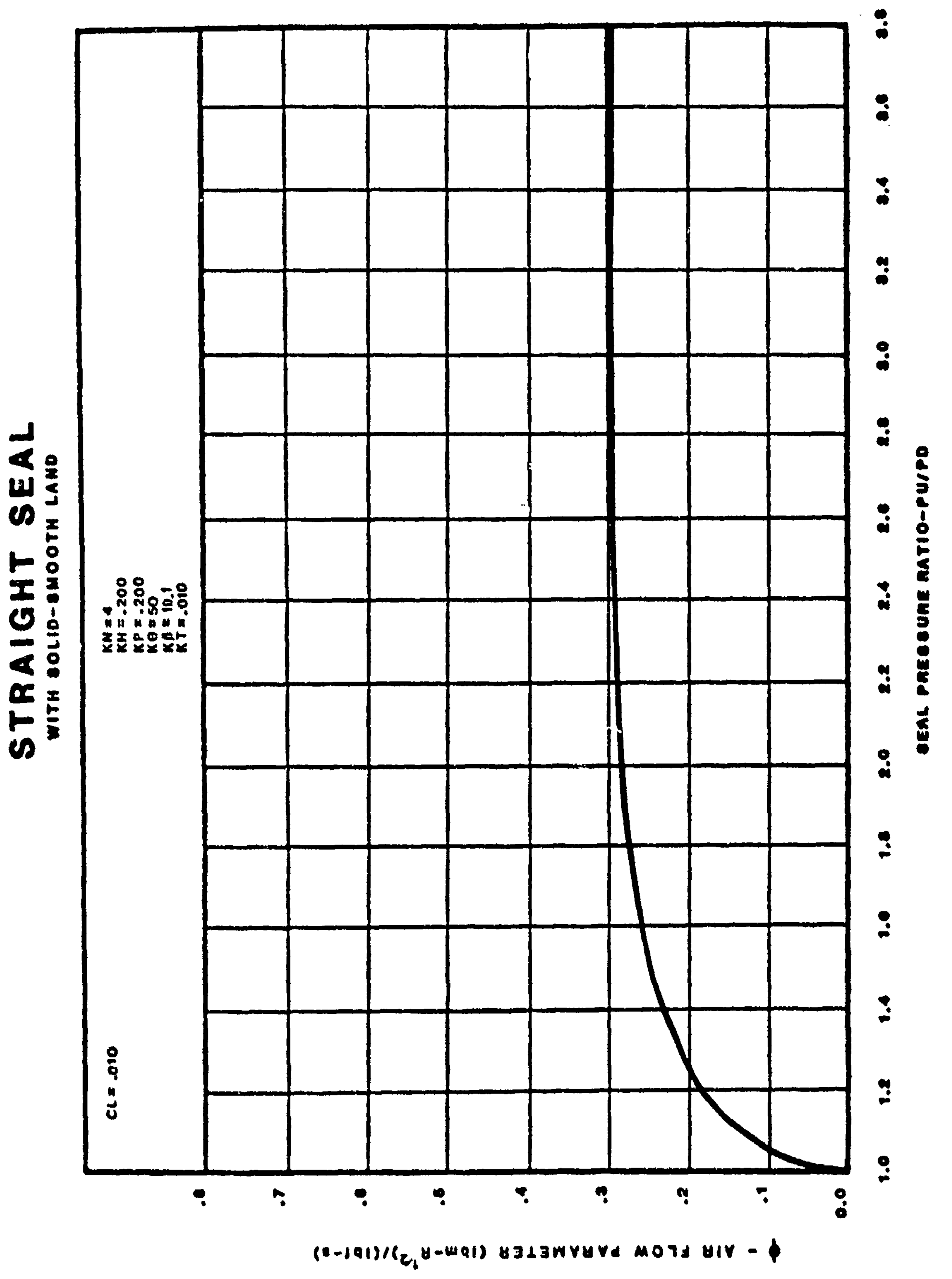
B.1.1 Full-Scale Seals

The full-scale seal dimensions are typical of medium to large gas turbine engines. These test results formed a part of the data bank for the Design Model development.

STRAIGHT SEAL

WITH SOLID-SMOOTH LAND

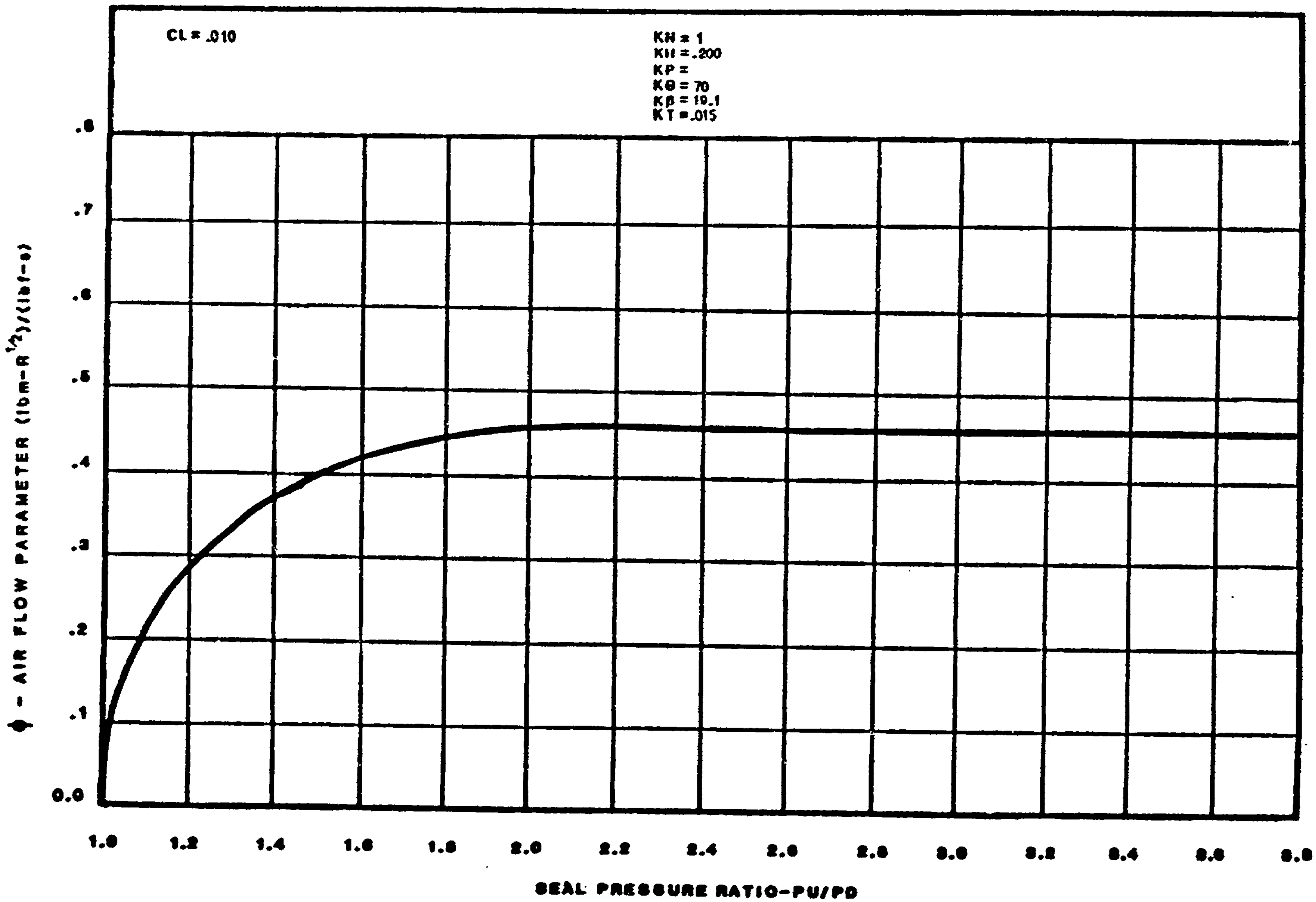




STRAIGHT SEAL
WITH SOLID-SMOOTH LAND
CL = .010
KN = 4
KH = .200
KP = .200
Kθ = 50
Kβ = 10.1
KT = .010
ϕ - AIR FLOW PARAMETER (lbm-R½)/(lbf-s)
SEAL PRESSURE RATIO-PU/PD

STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



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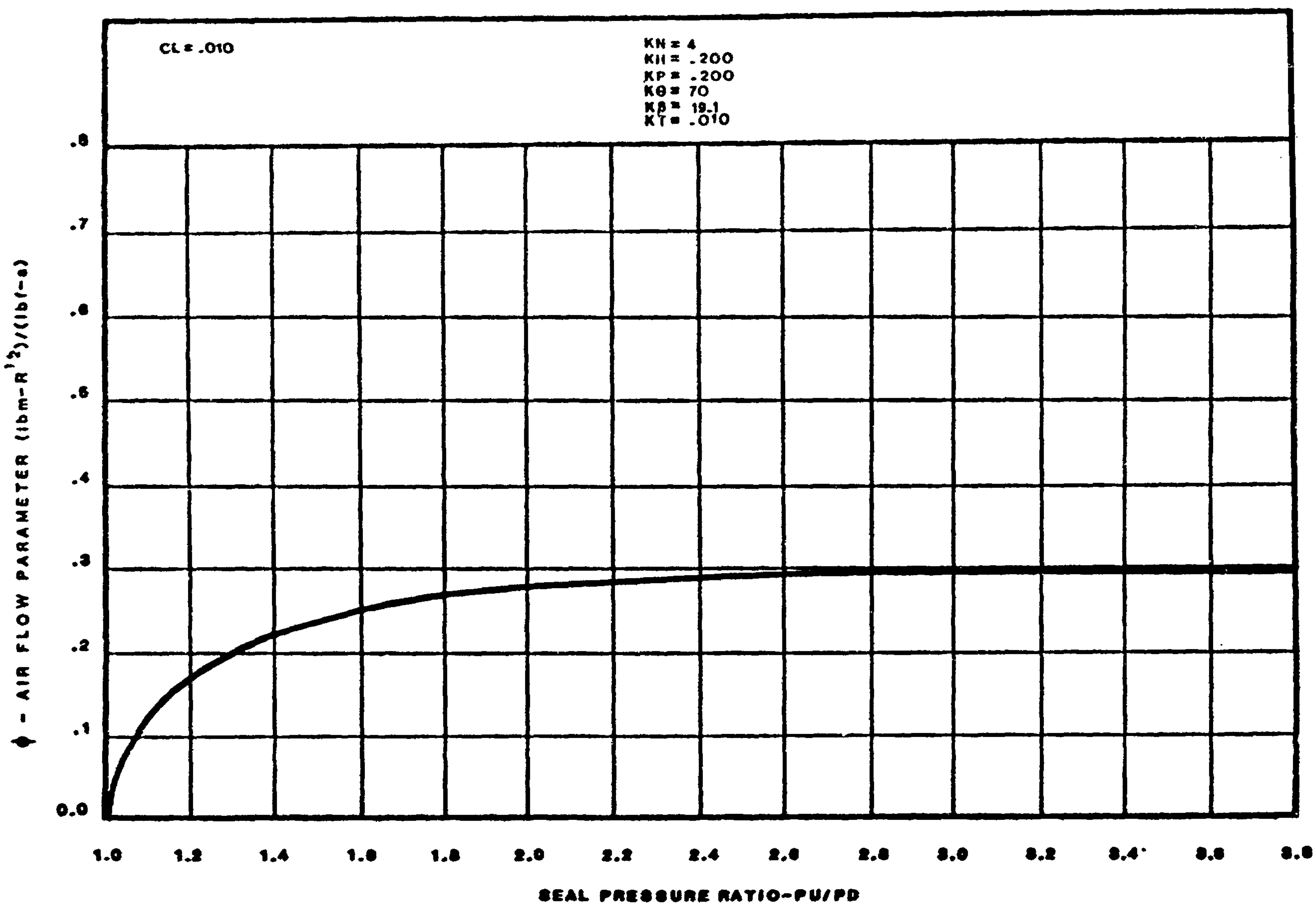
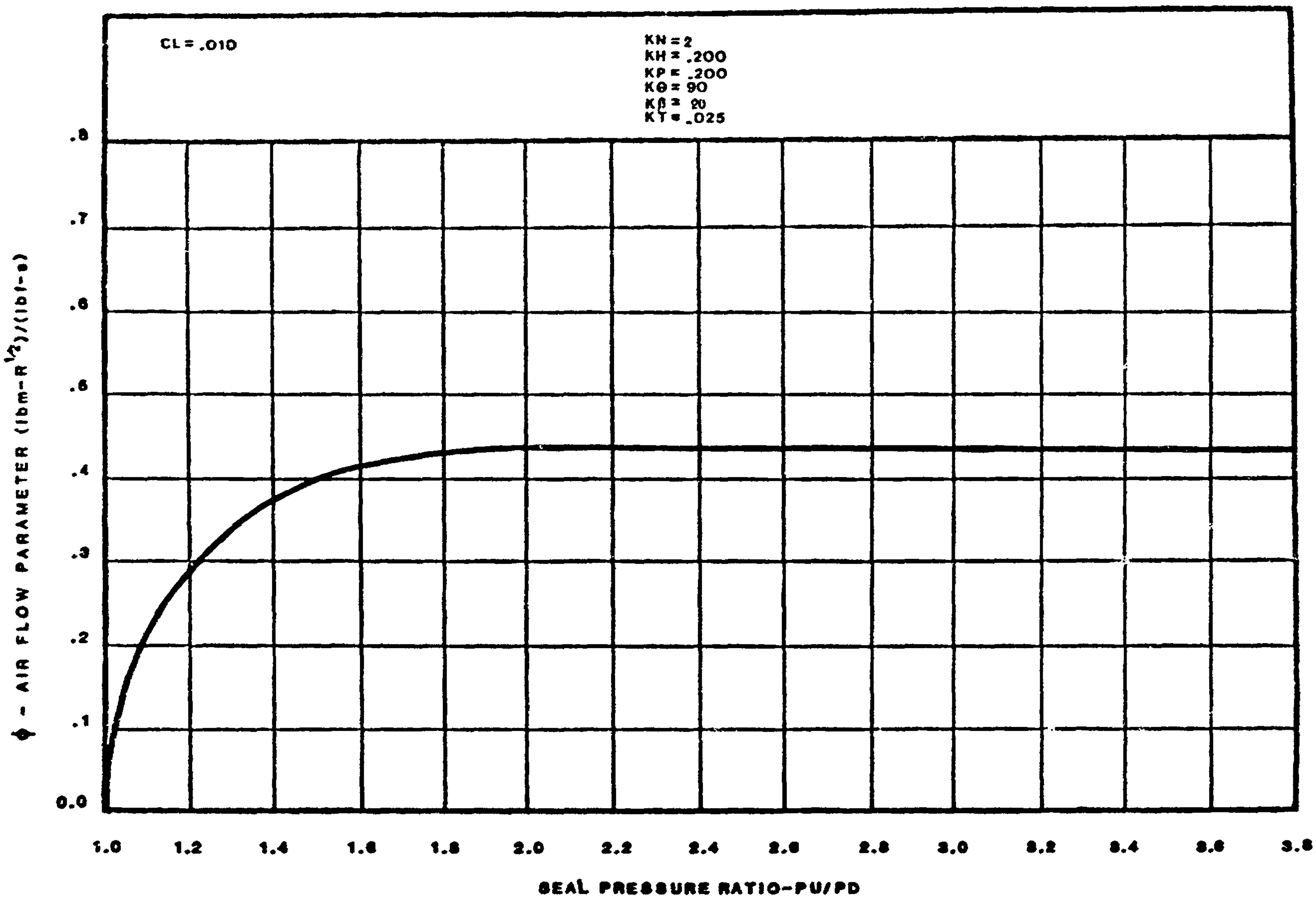
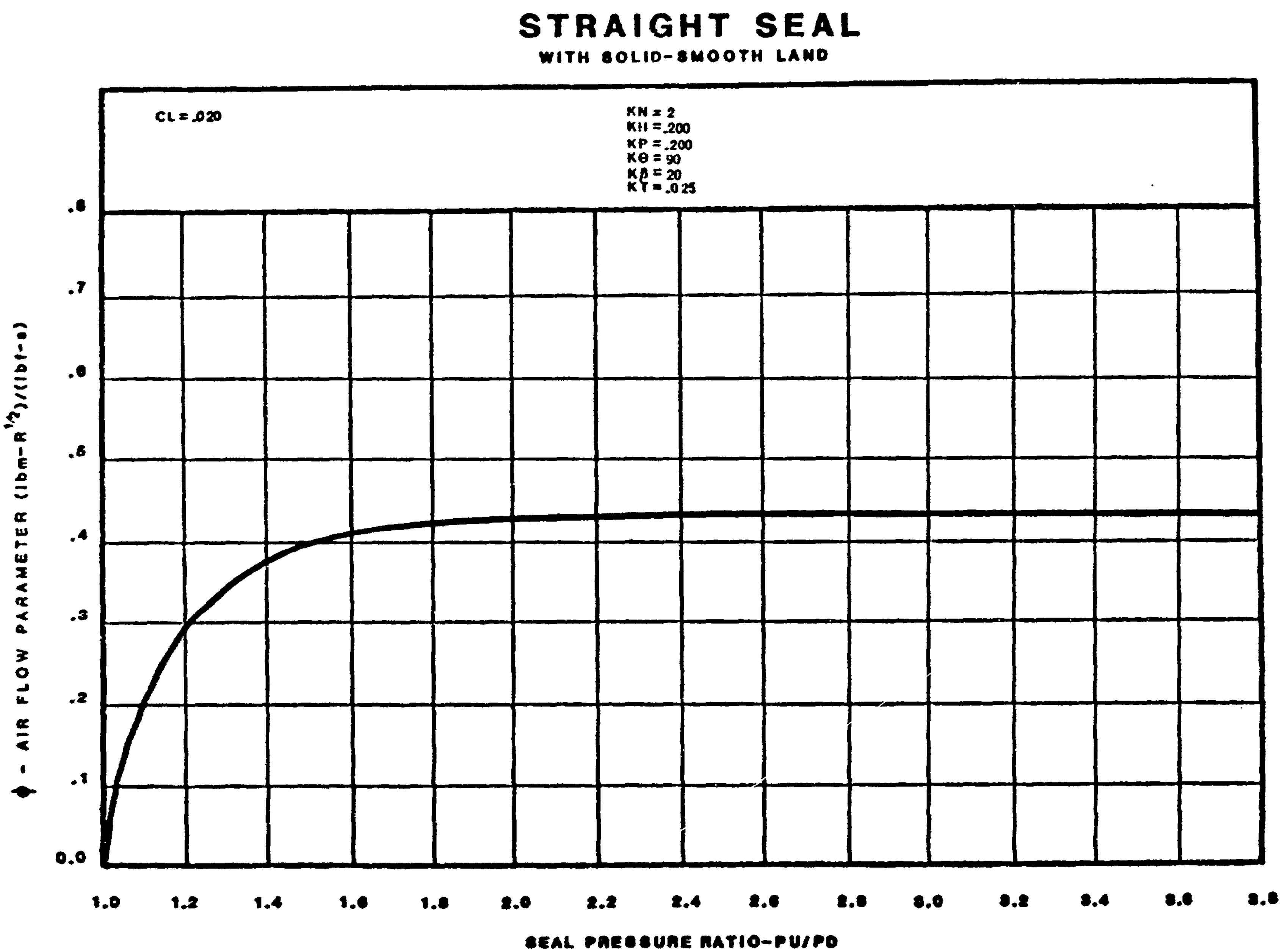
WITH SOLID-SMOOTH LAND



STRAIGHT SEAL

WITH SOLID- SMOOTH LAND

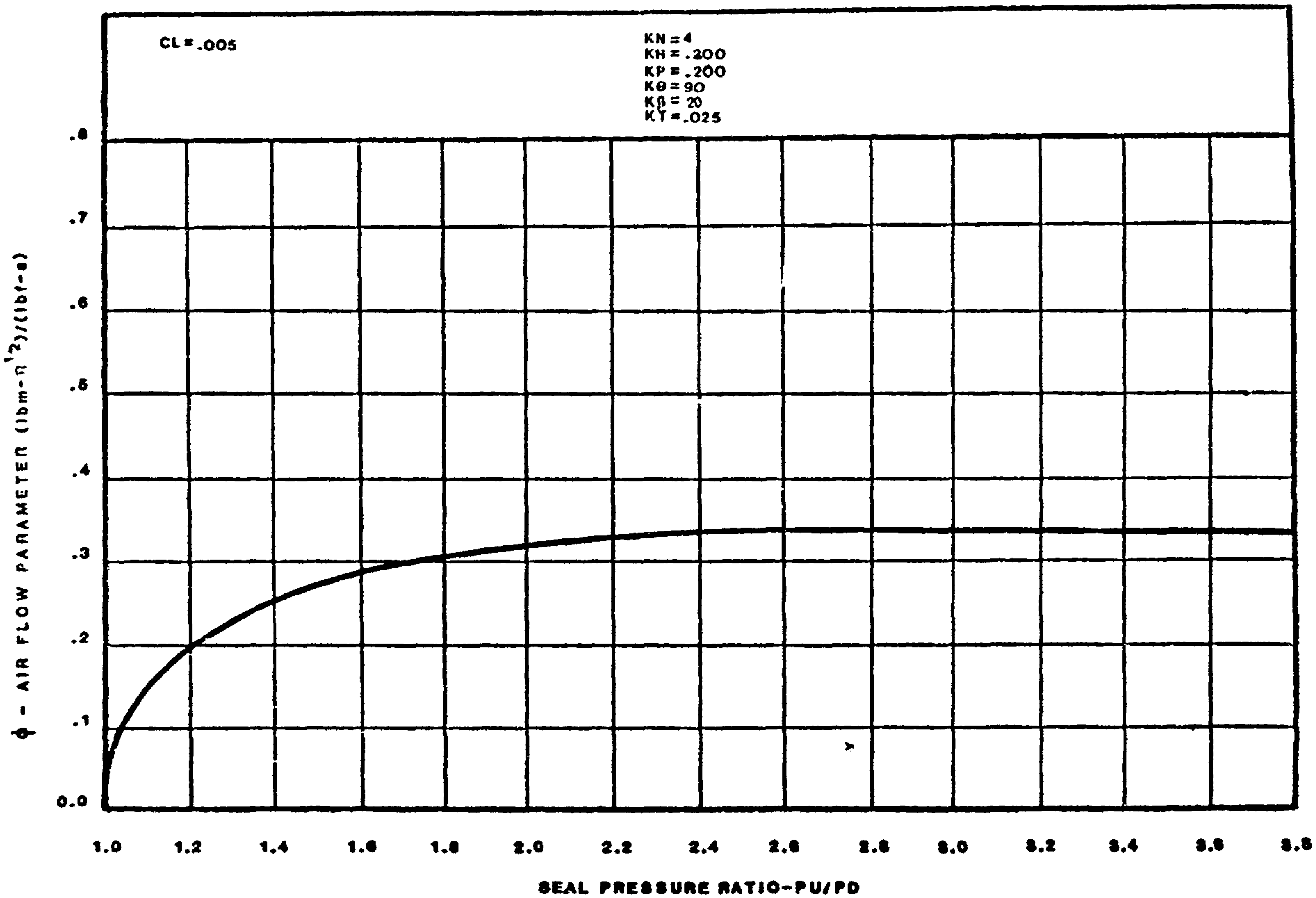




STRAIGHT SEAL
WITH SOLID-SMOOTH LAND
CL = .020
KN = 2
KH = .200
KP = .200
Kθ = 90
Kβ = 20
KT = .025
.8
.7
.6
.5
.4
.3
.2
.1
0.0
ϕ - AIR FLOW PARAMETER (lbm-R^1/2)/(lbf-s)
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
SEAL PRESSURE RATIO-PU/PD

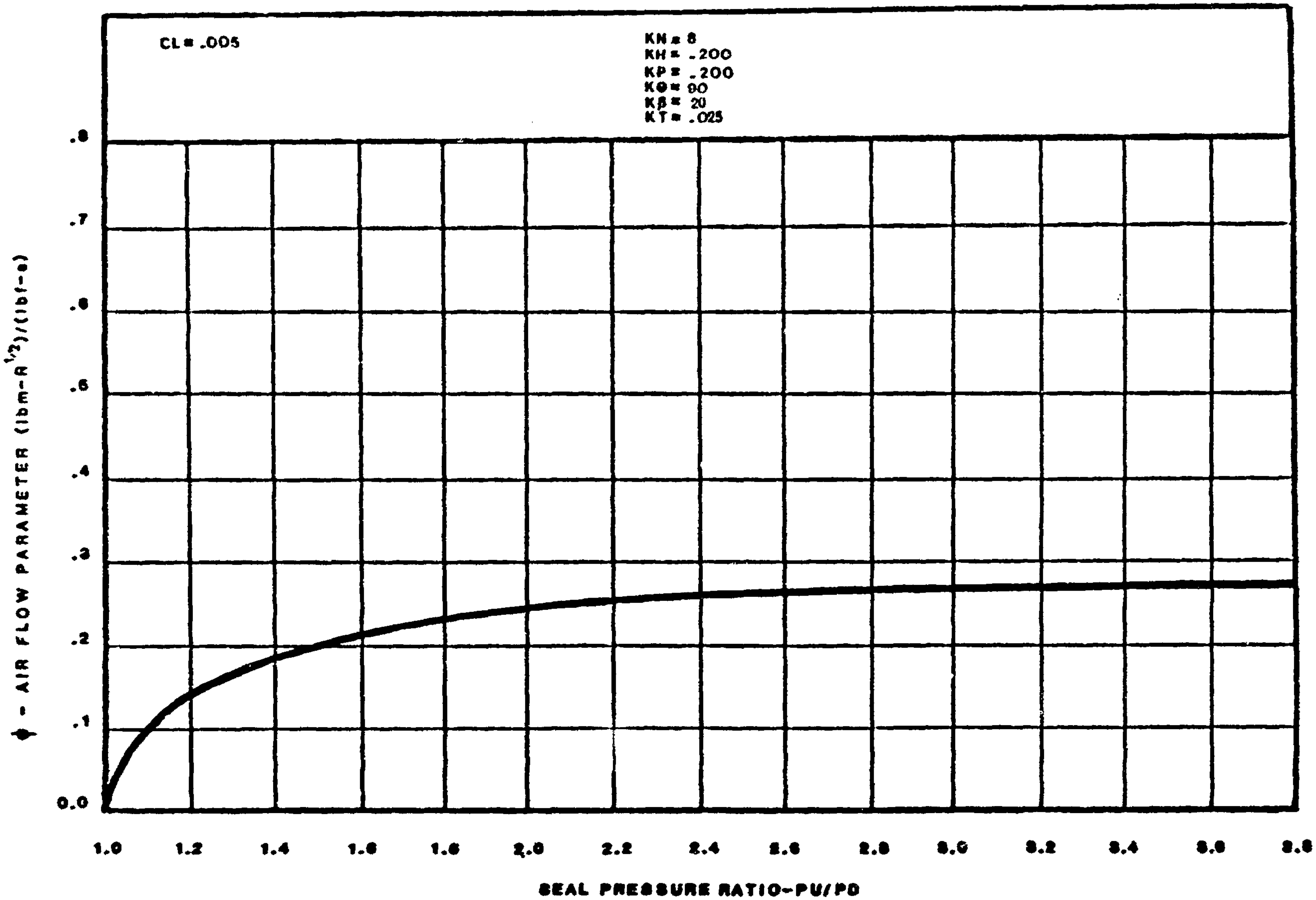
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



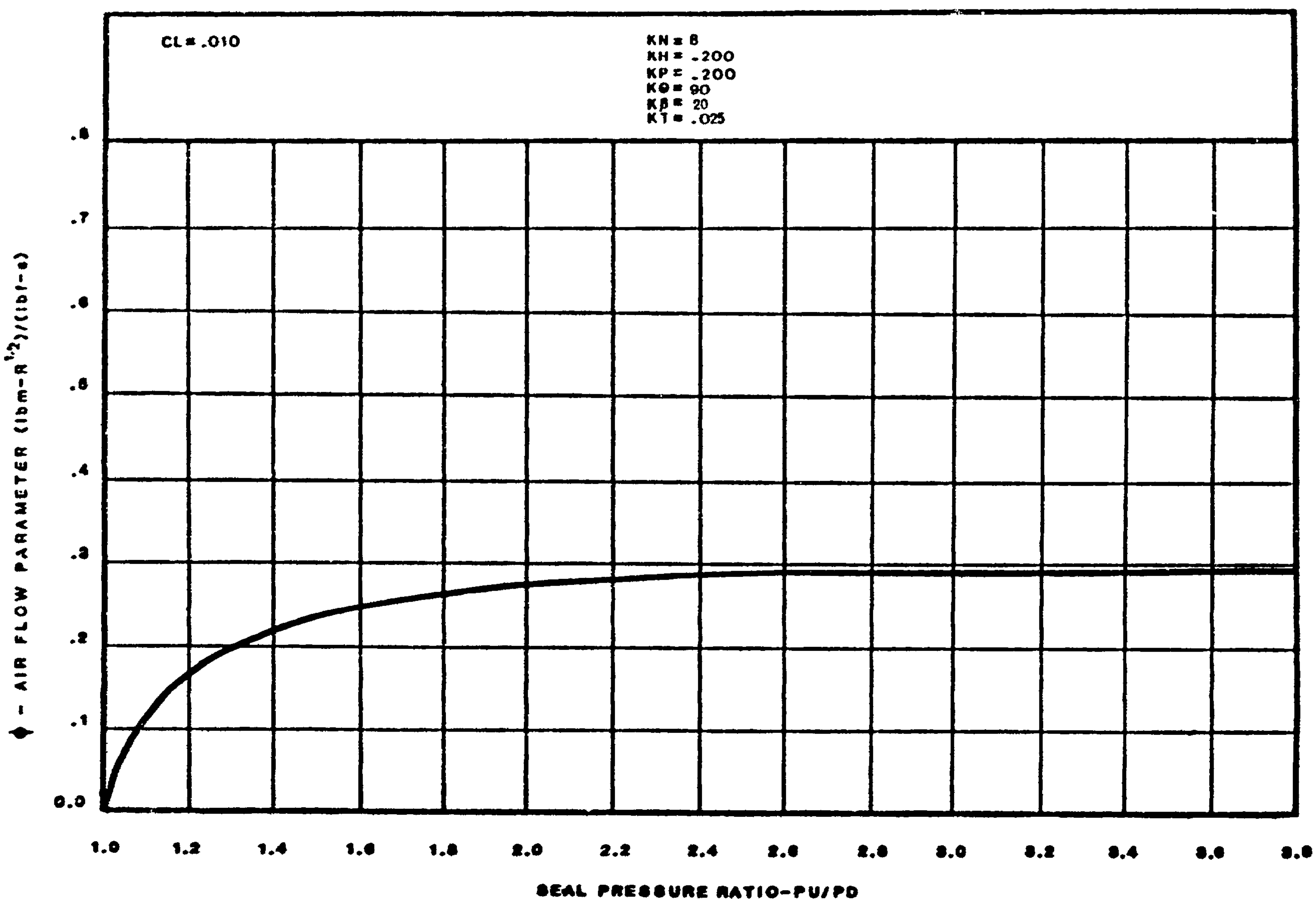
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



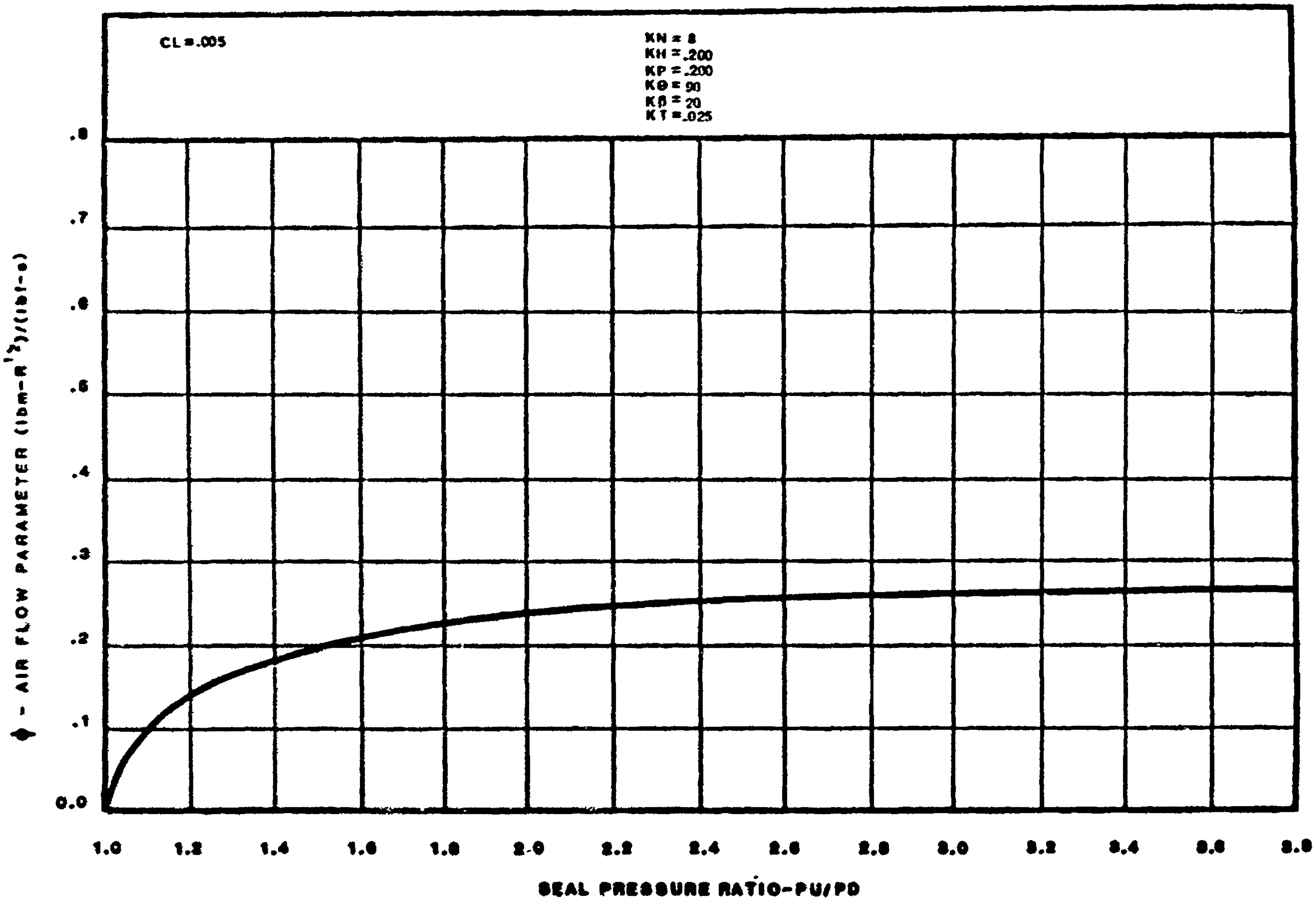
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



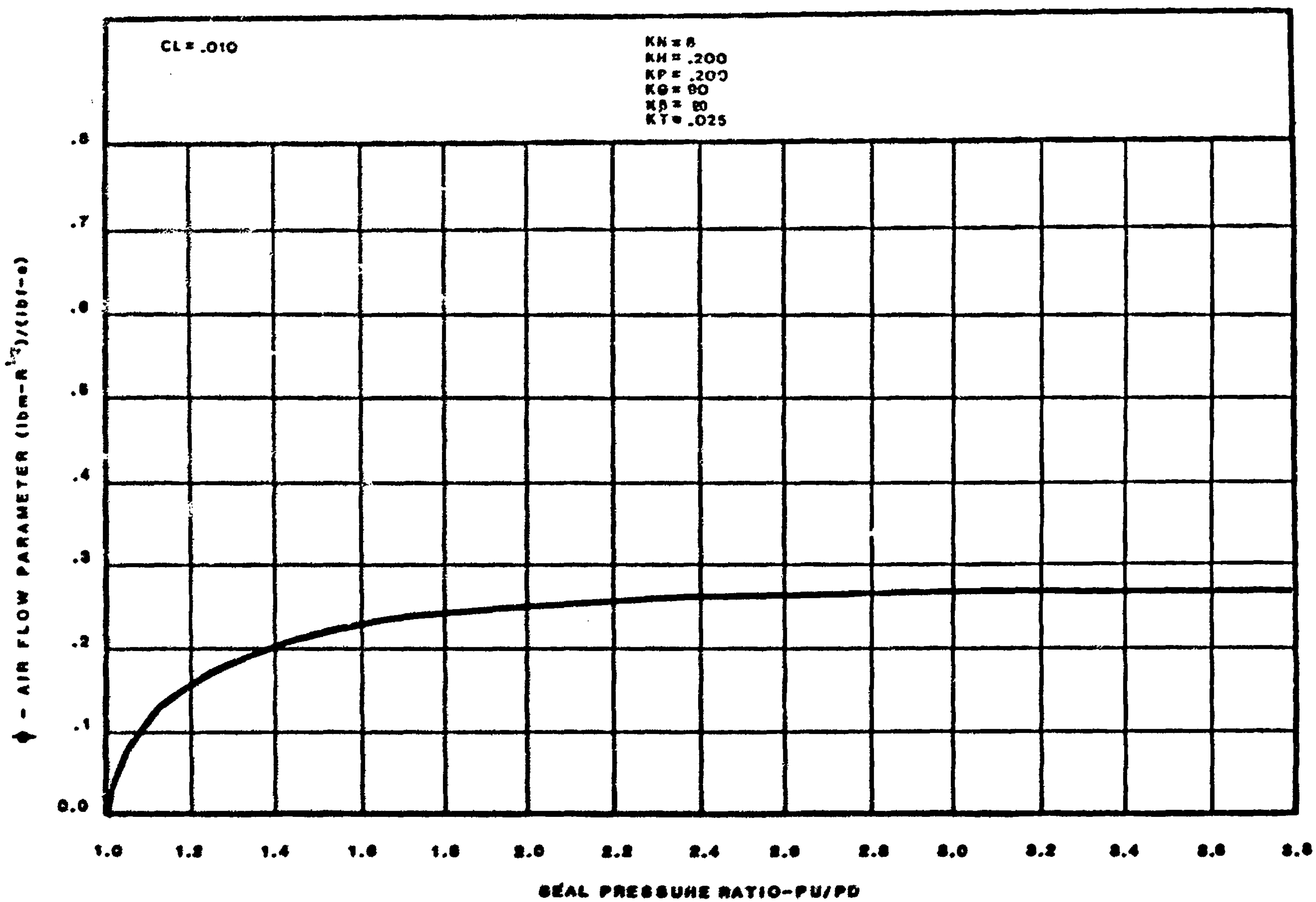
STRAIGHT SEAL

WITH SOLID- ROUGH LAND

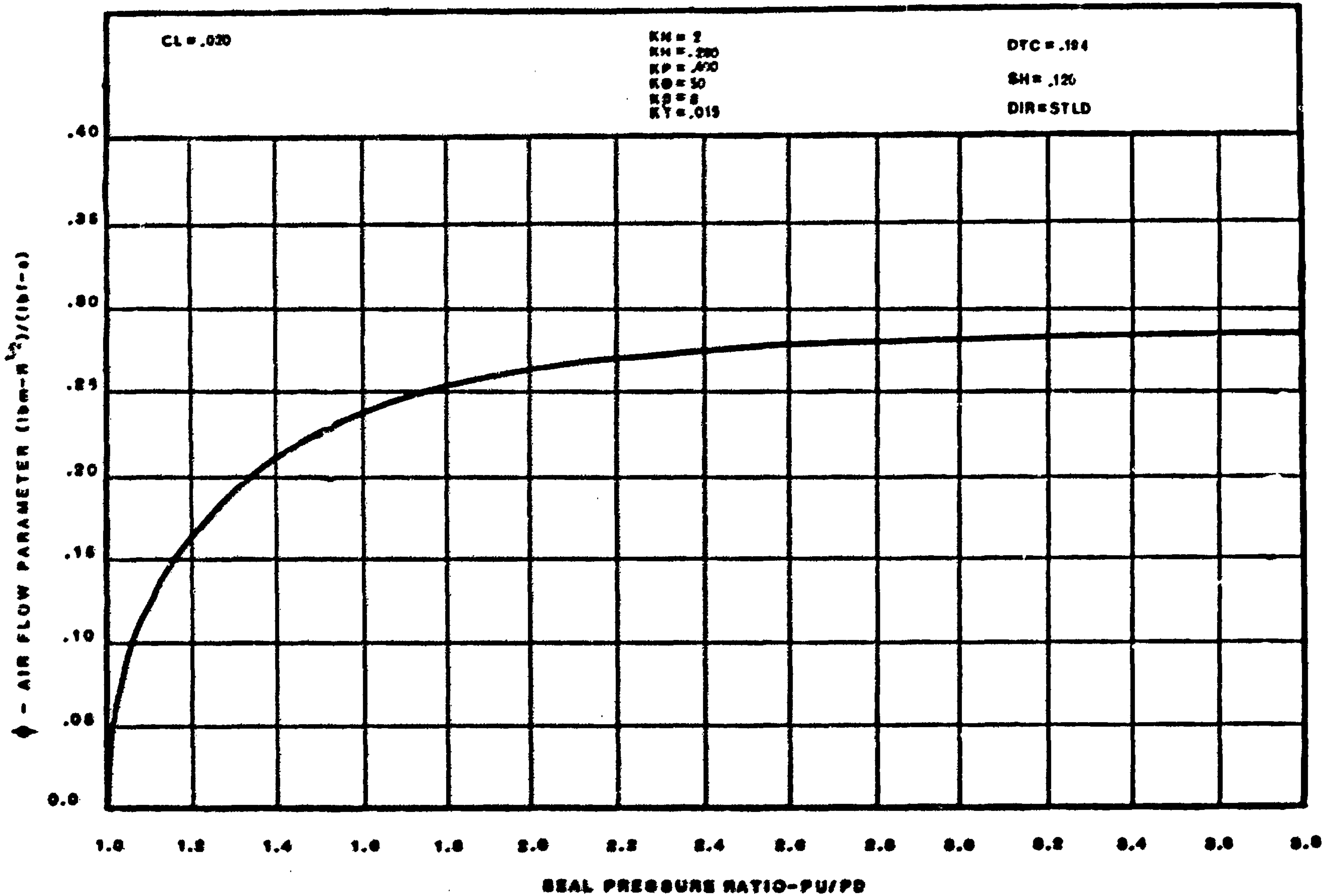


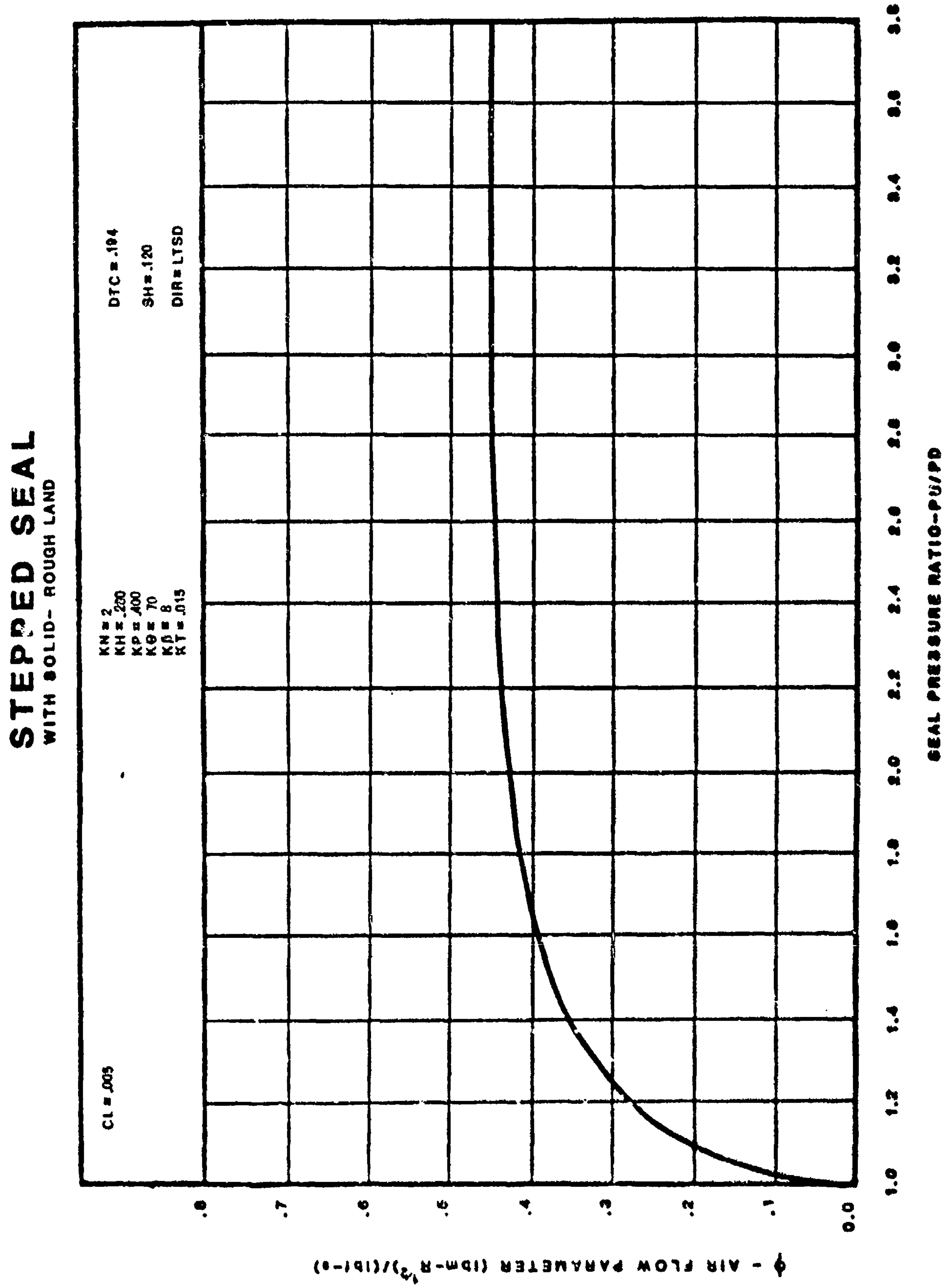
STRAIGHT SEAL

WITH SOLID- ROUGH LAND

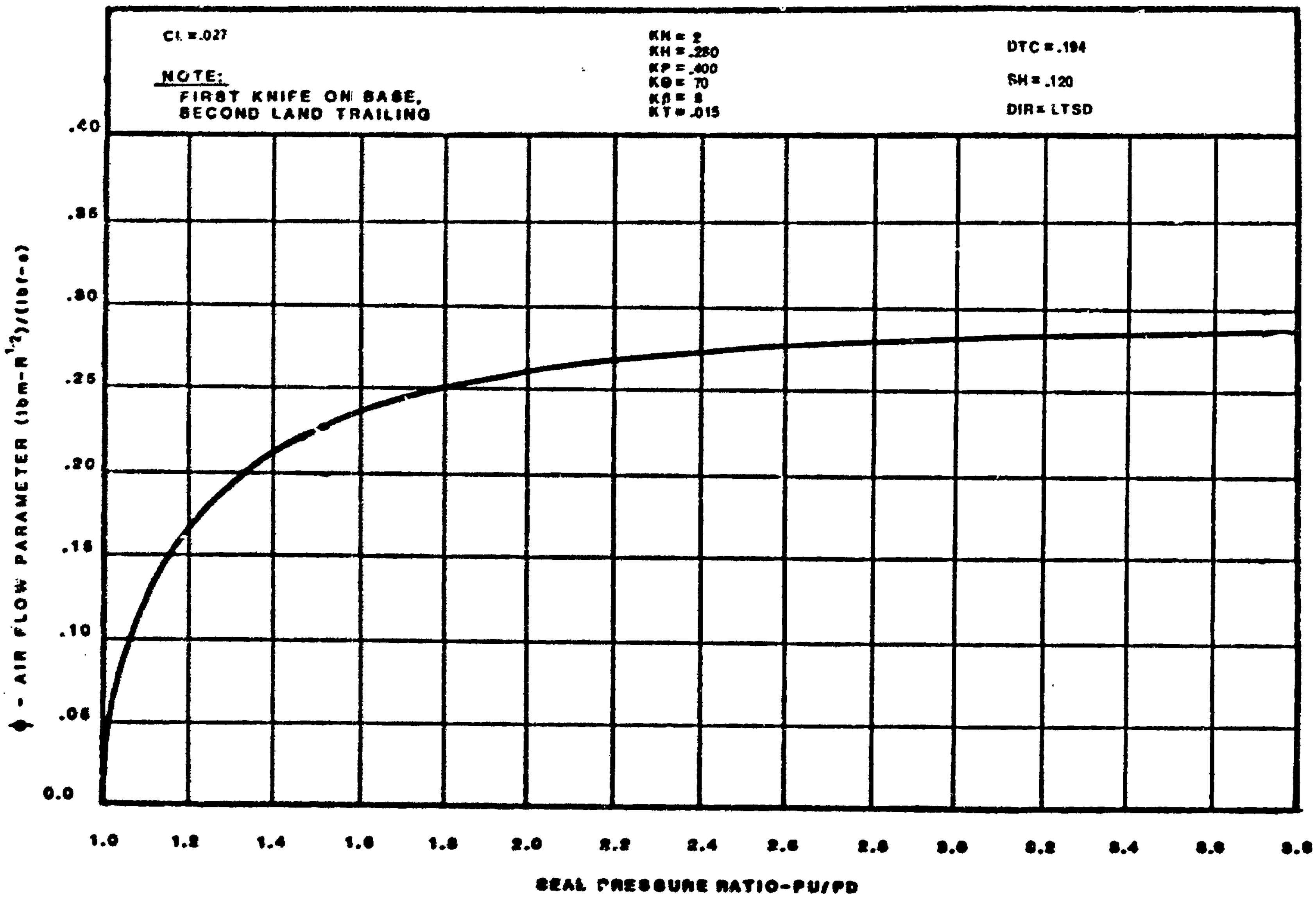


STEPPED SEAL
WITH SOLID-SMOOTH LAND



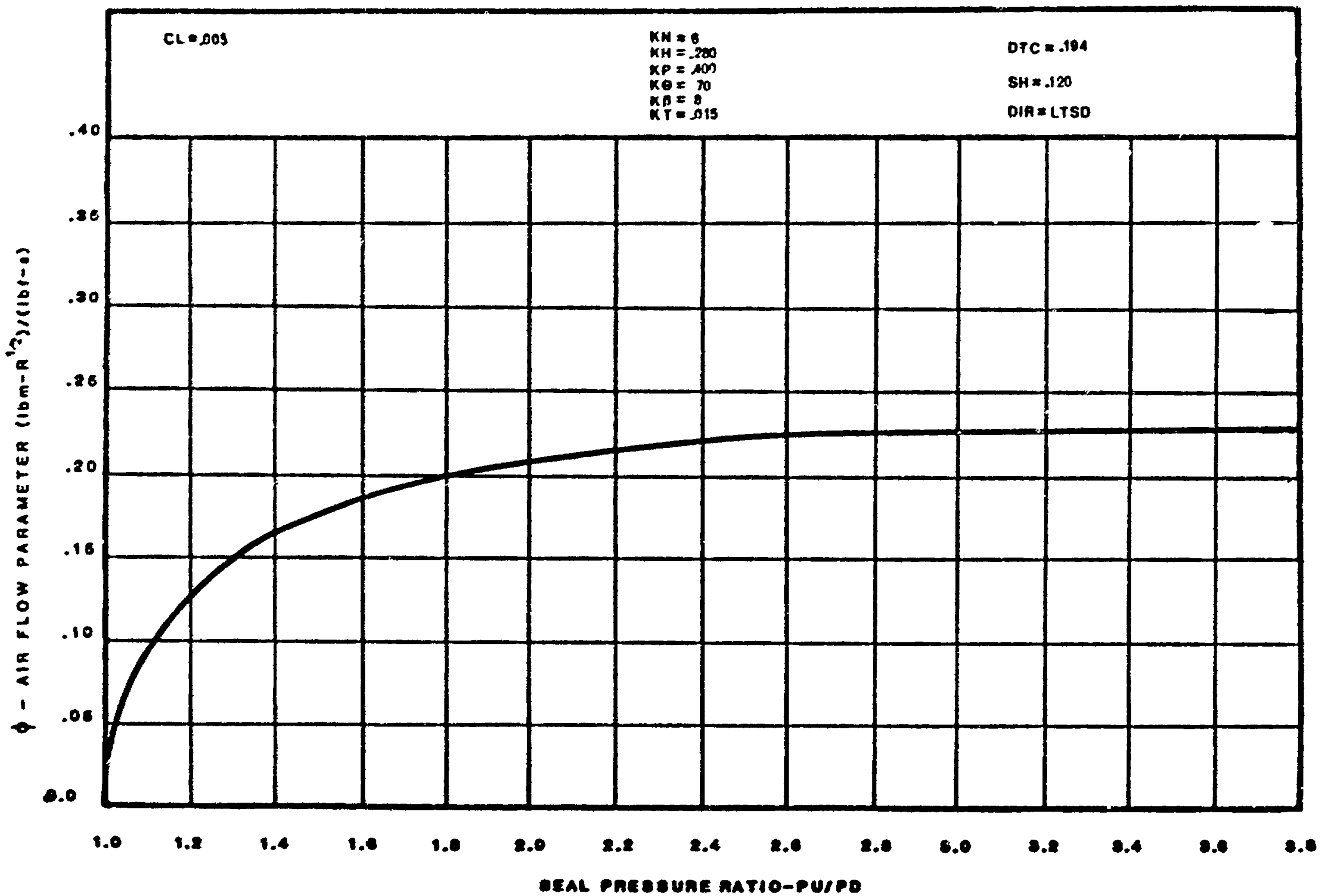

STEPPED SEAL
WITH SOLID- ROUGH LAND
CL = .005
KN = 2
KH = .220
KP = .400
Kθ = 70
Kβ = 8
KT = .015
DTC = .194
SH = .120
DIR = LTSD
φ - AIR FLOW PARAMETER (lbm-R^½)/(lbf-s)
SEAL PRESSURE RATIO-PU/PD
0.0
.1
.2
.3
.4
.5
.6
.7
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8

STEPPED SEAL
WITH SOLID-SMOOTH LAND

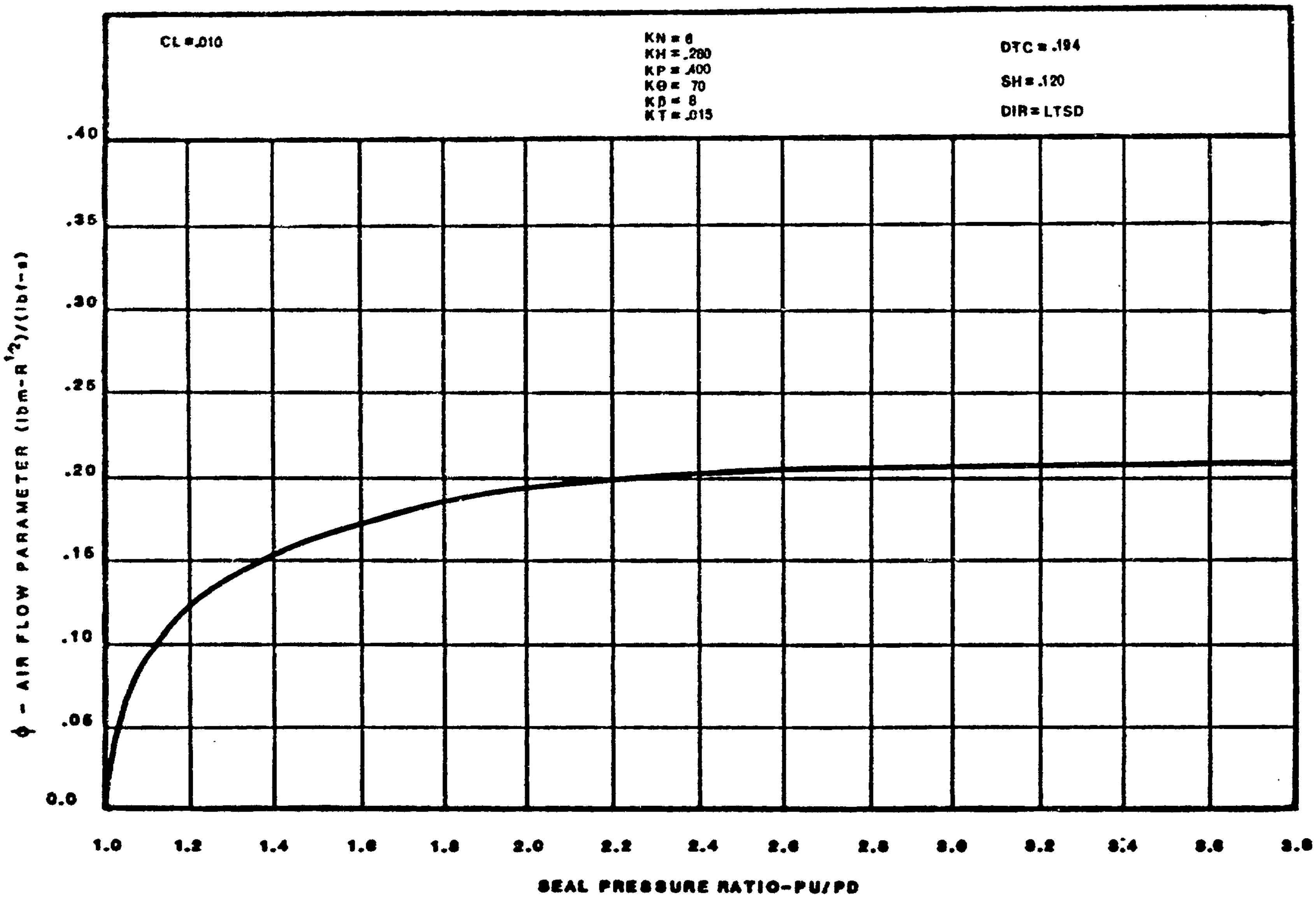


STEPPED SEAL

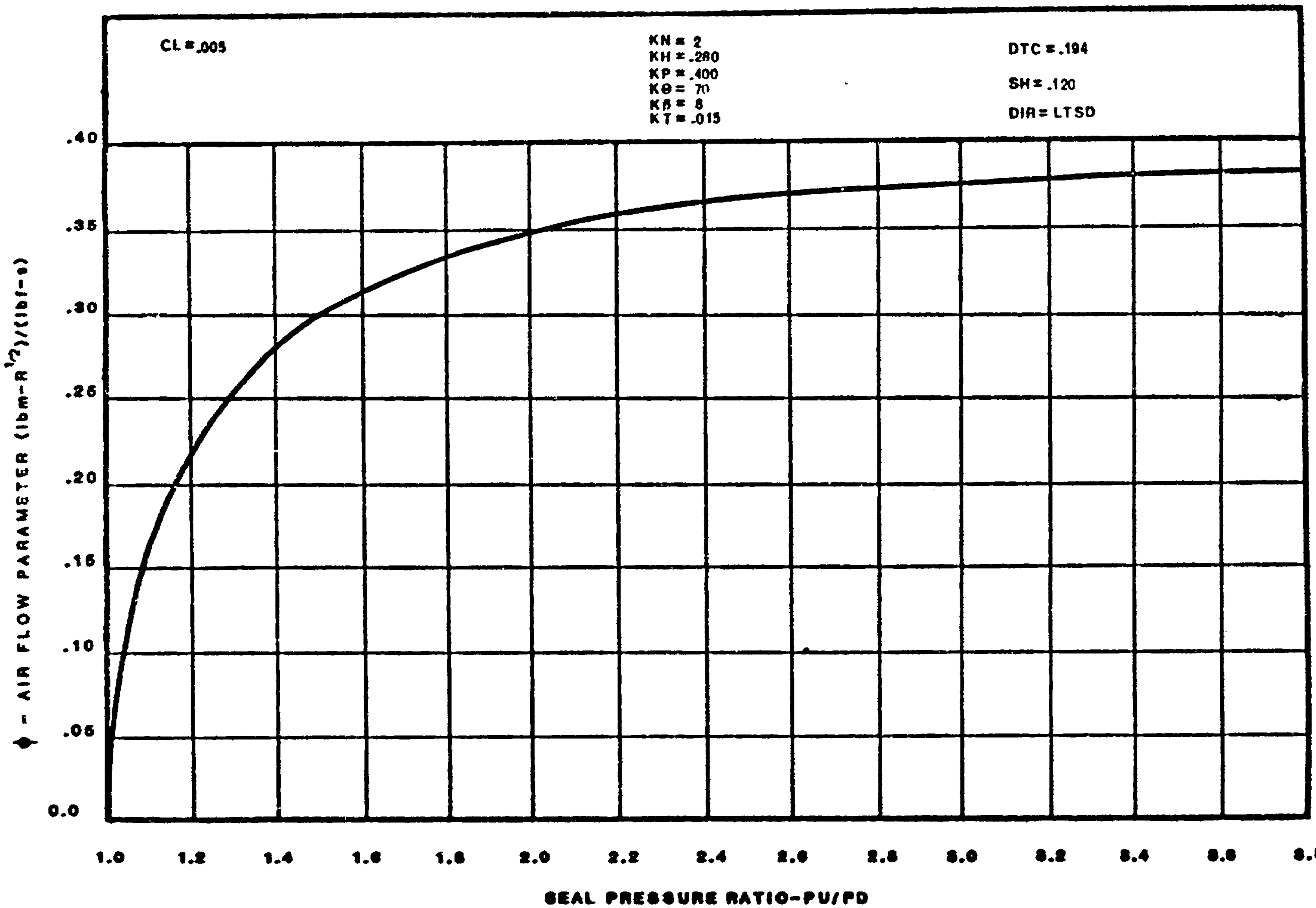
WITH SOLID- SMOOTH LAND



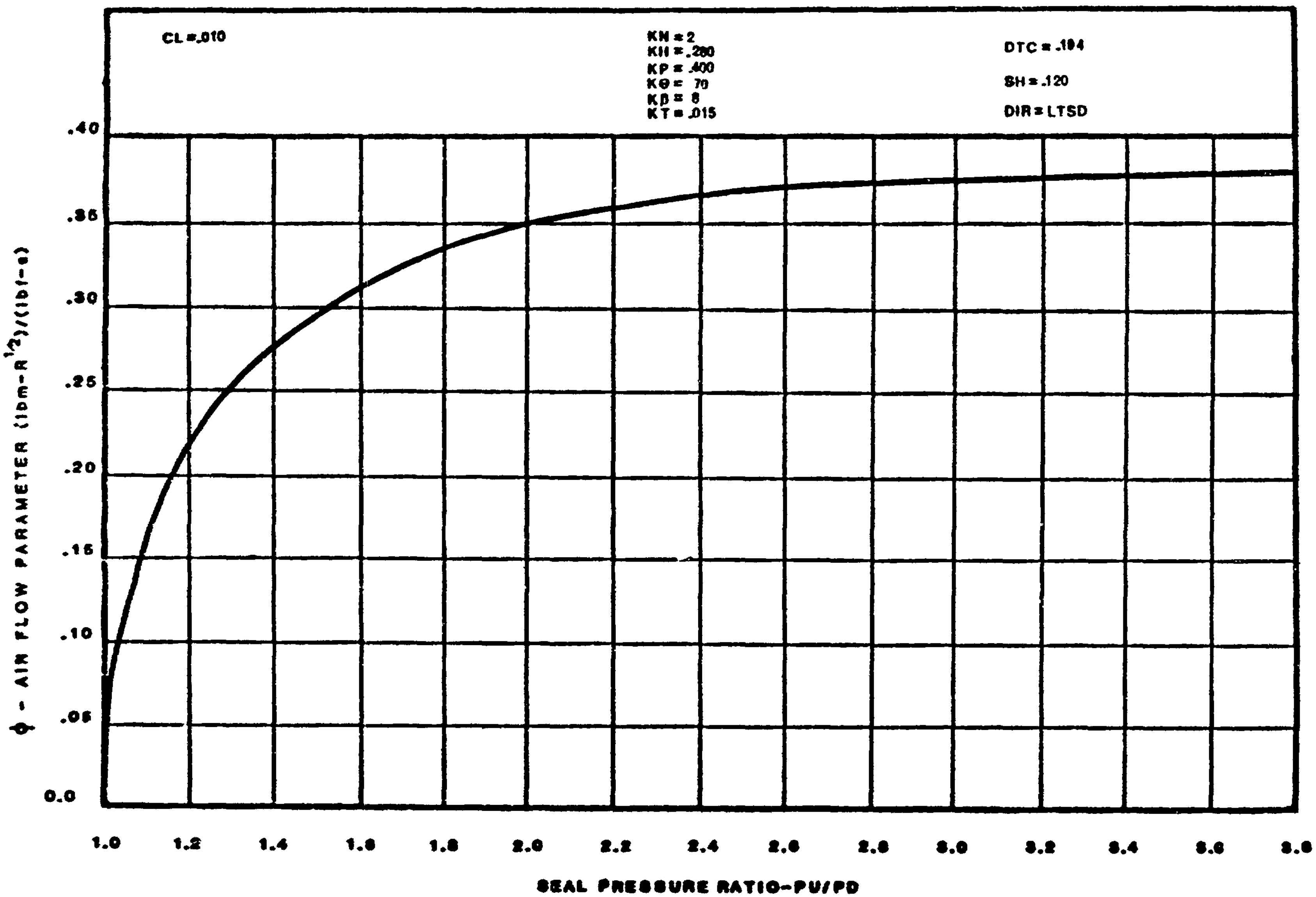
STEPPED SEAL
WITH SOLID- SMOOTH LAND

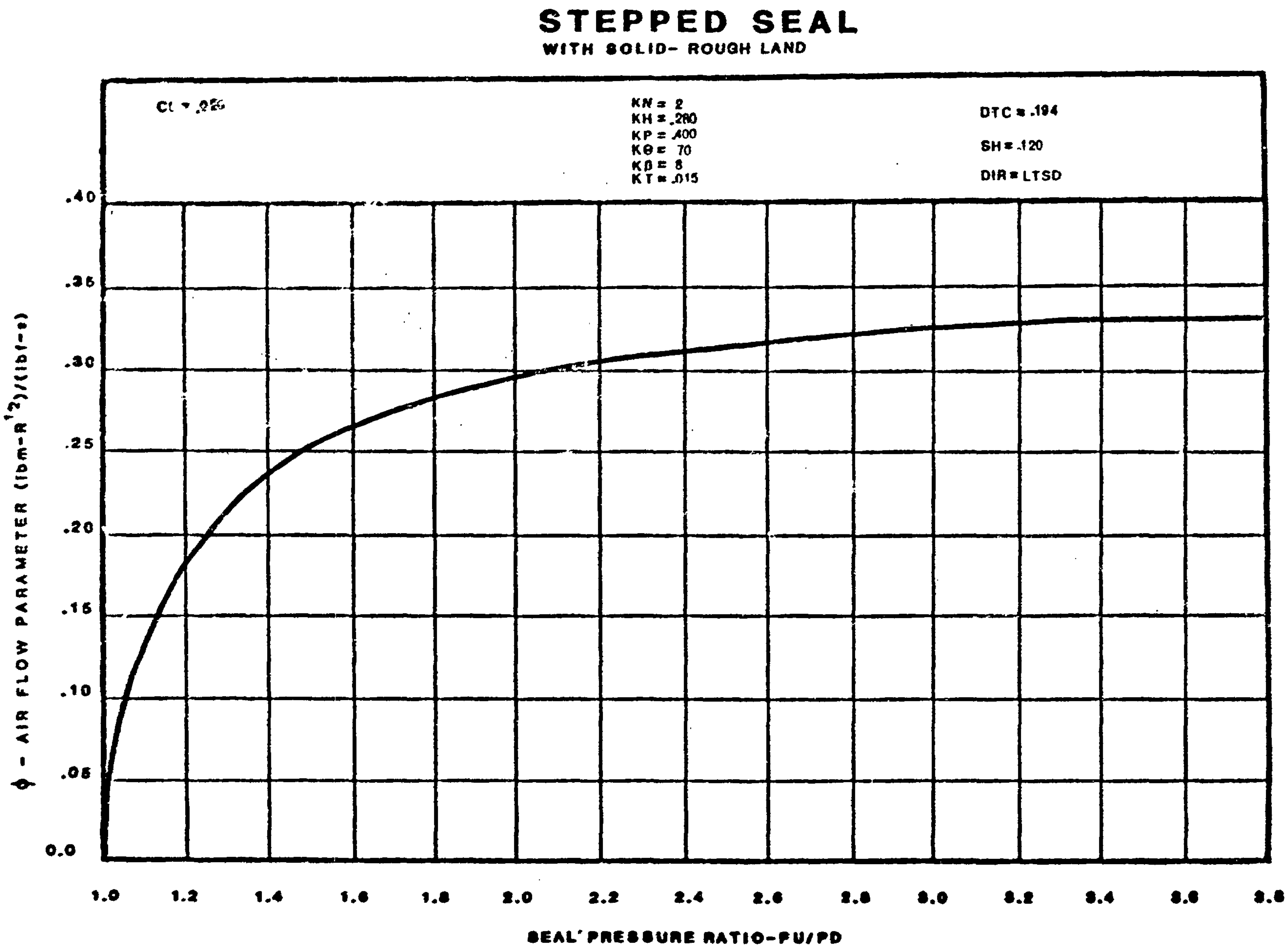


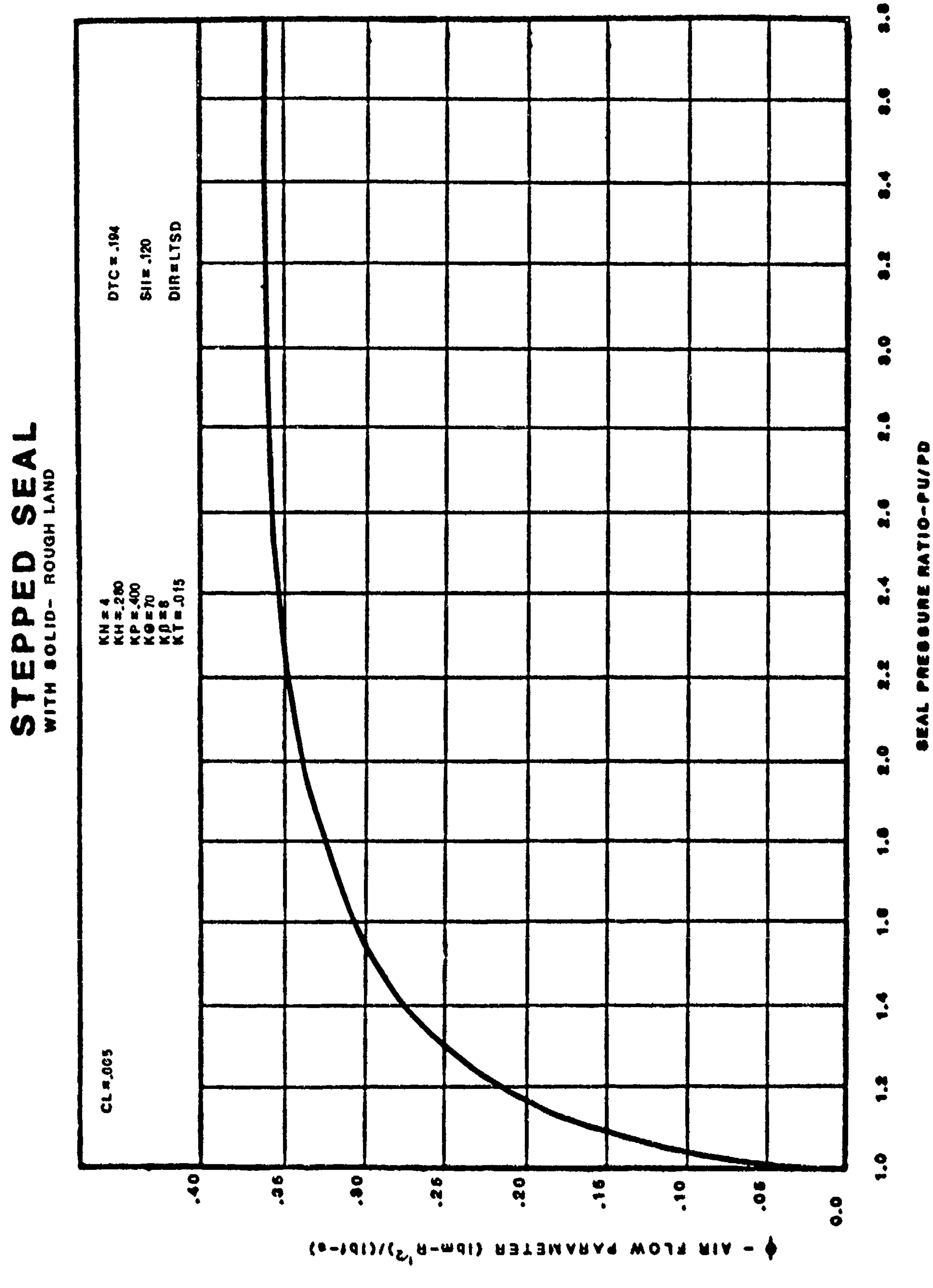
STEPPED SEAL
WITH SOLID-SMOOTH LAND



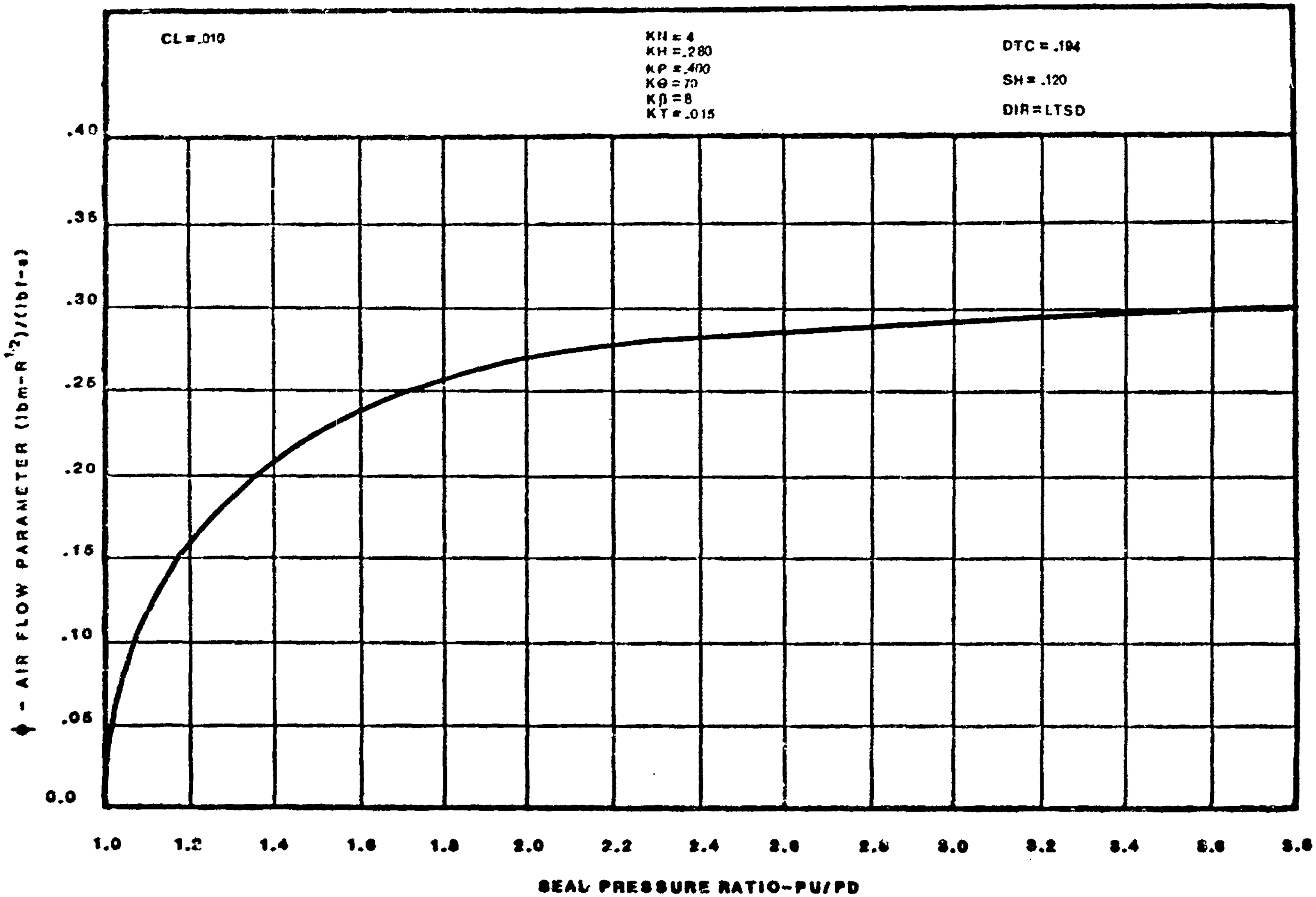
STEPPED SEAL
WITH SOLID- ROUGH LAND




STEPPED SEAL
WITH SOLID- ROUGH LAND
CL = .025
KN = 2
KH = .280
KP = .400
Kθ = 70
Kβ = 8
KT = .015
DTC = .194
SH = .120
DIR = LTSD
.40
.35
.30
.25
.20
.15
.10
.05
0.0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
SEAL PRESSURE RATIO-PU/PD
φ - AIR FLOW PARAMETER (lbm-R^½)/(lbf-s)

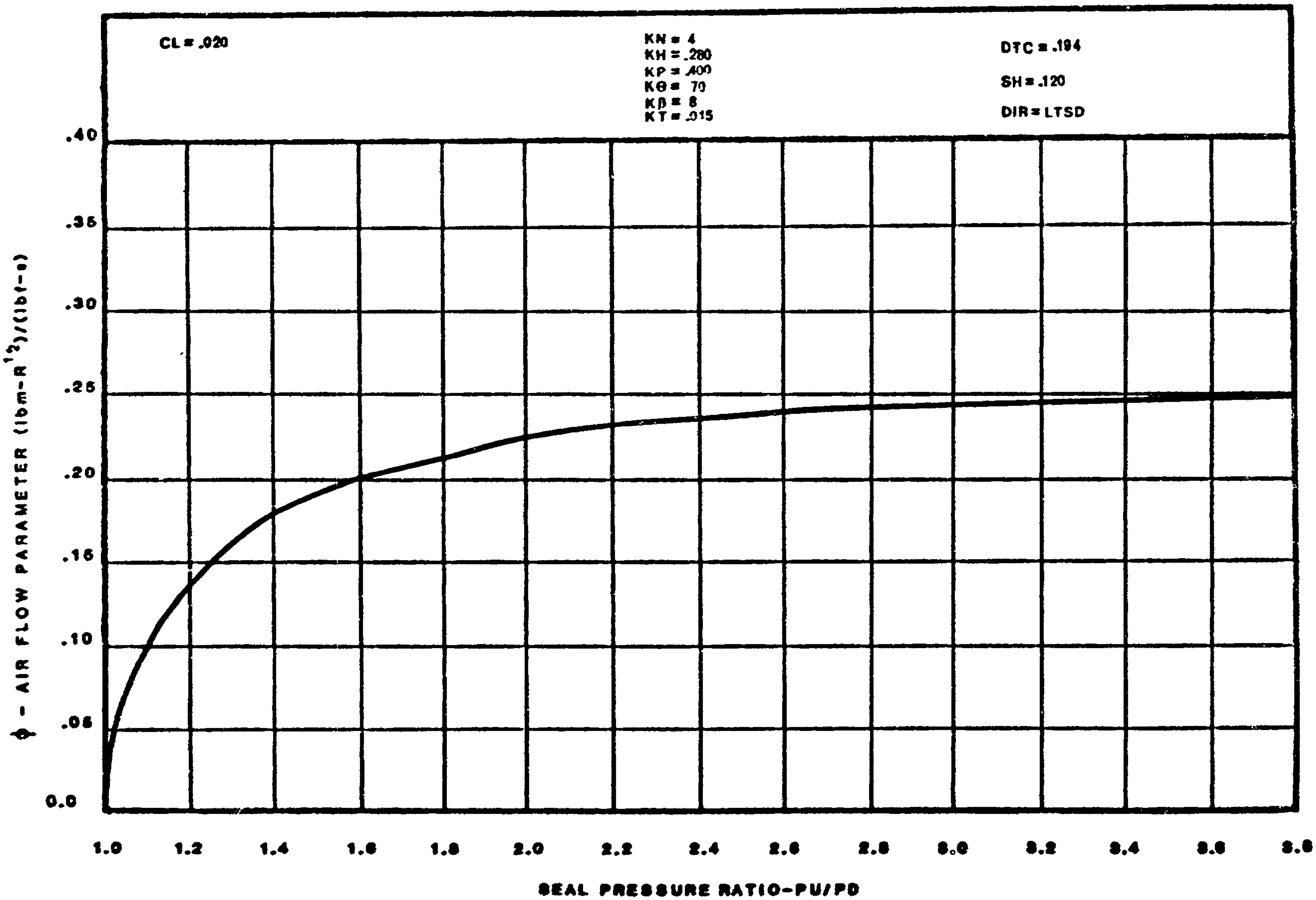

STEPPED SEAL
WITH SOLID- ROUGH LAND
CL=.005
KN=4
KH=.280
KP=.400
Kθ=70
Kβ=8
KT=.015
DTC=.194
SII=.120
DIR=LTSD
φ - AIR FLOW PARAMETER (lbm-R^1/2)/(lbf-s)
0.0
.05
.10
.15
.20
.25
.30
.35
.40
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
SEAL PRESSURE RATIO-PU/PD

STEPPED SEAL
WITH SOLID- ROUGH LAND



STEPPED SEAL

WITH SOLID- ROUGH LAND



B.1.2 Large-Scale Seals

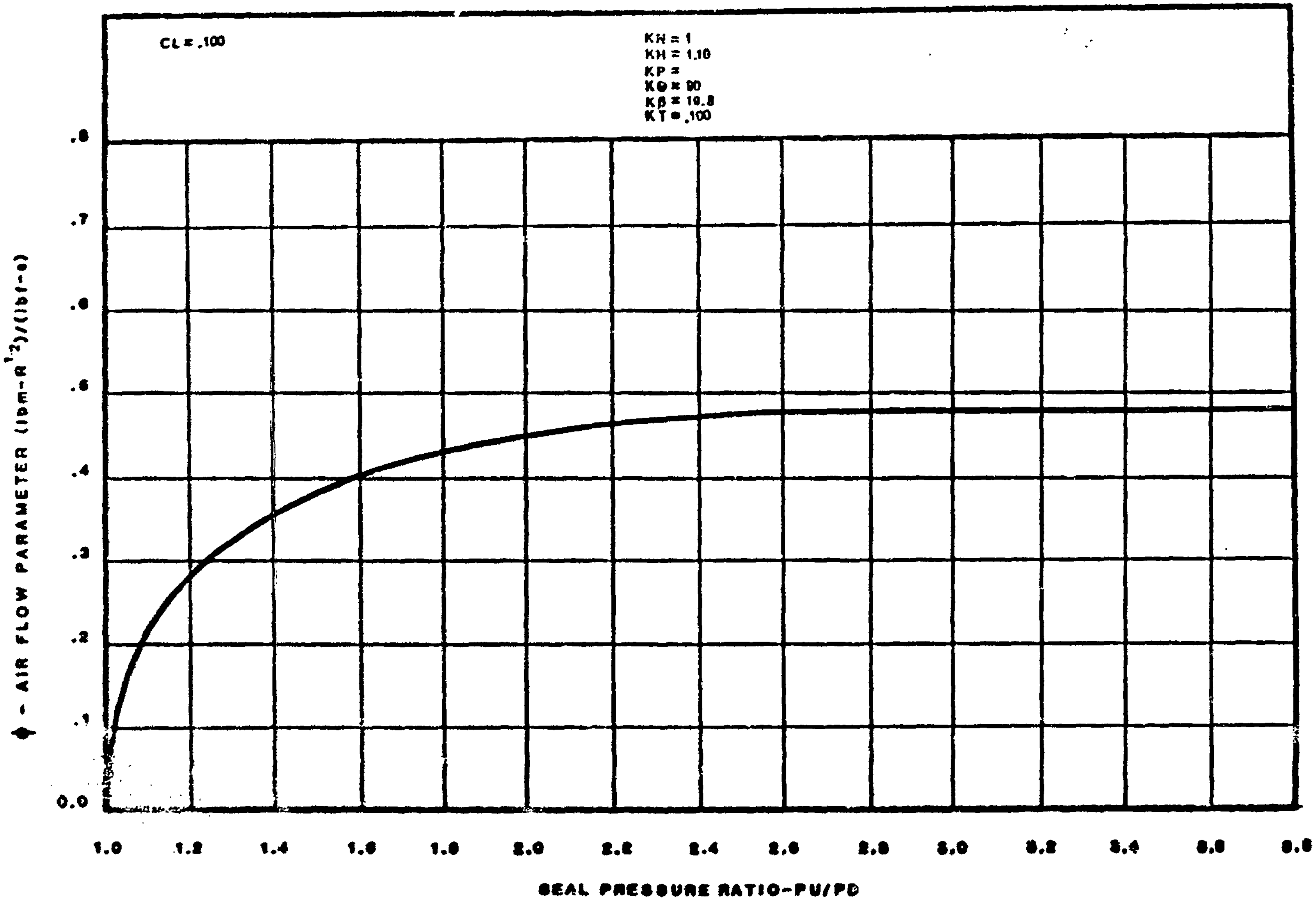
The large-scale seals were geometrically similar to full-scale seal configurations but were enlarged to the maximum model size acceptable to the 2-D rig:

Straight seals: 10 times full-scale
Stepped seals: 5 times full-scale

The performance data and interknife cavity pressure and temperature measurements were used to verify the accuracy of the Analysis Model predictions.

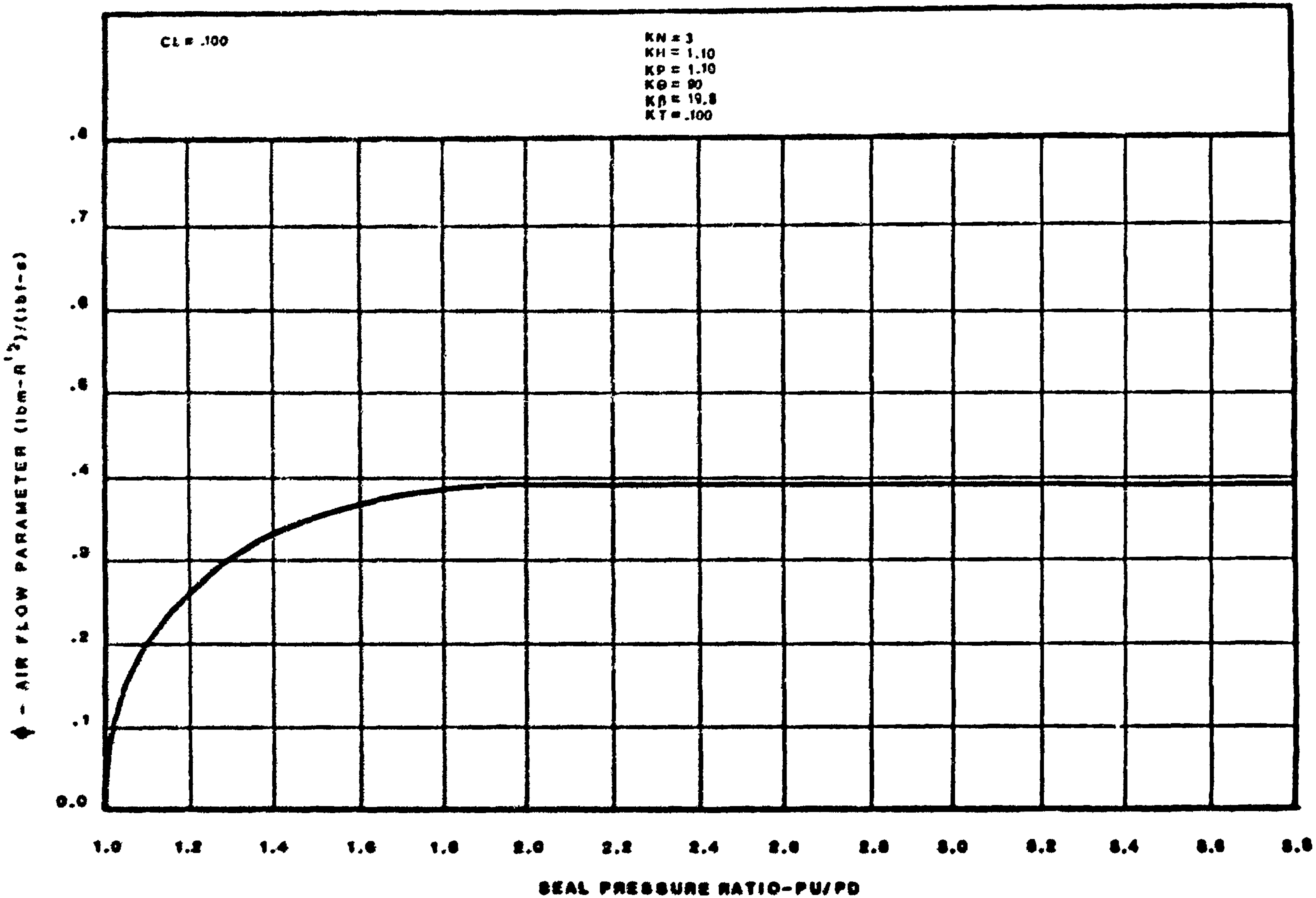
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



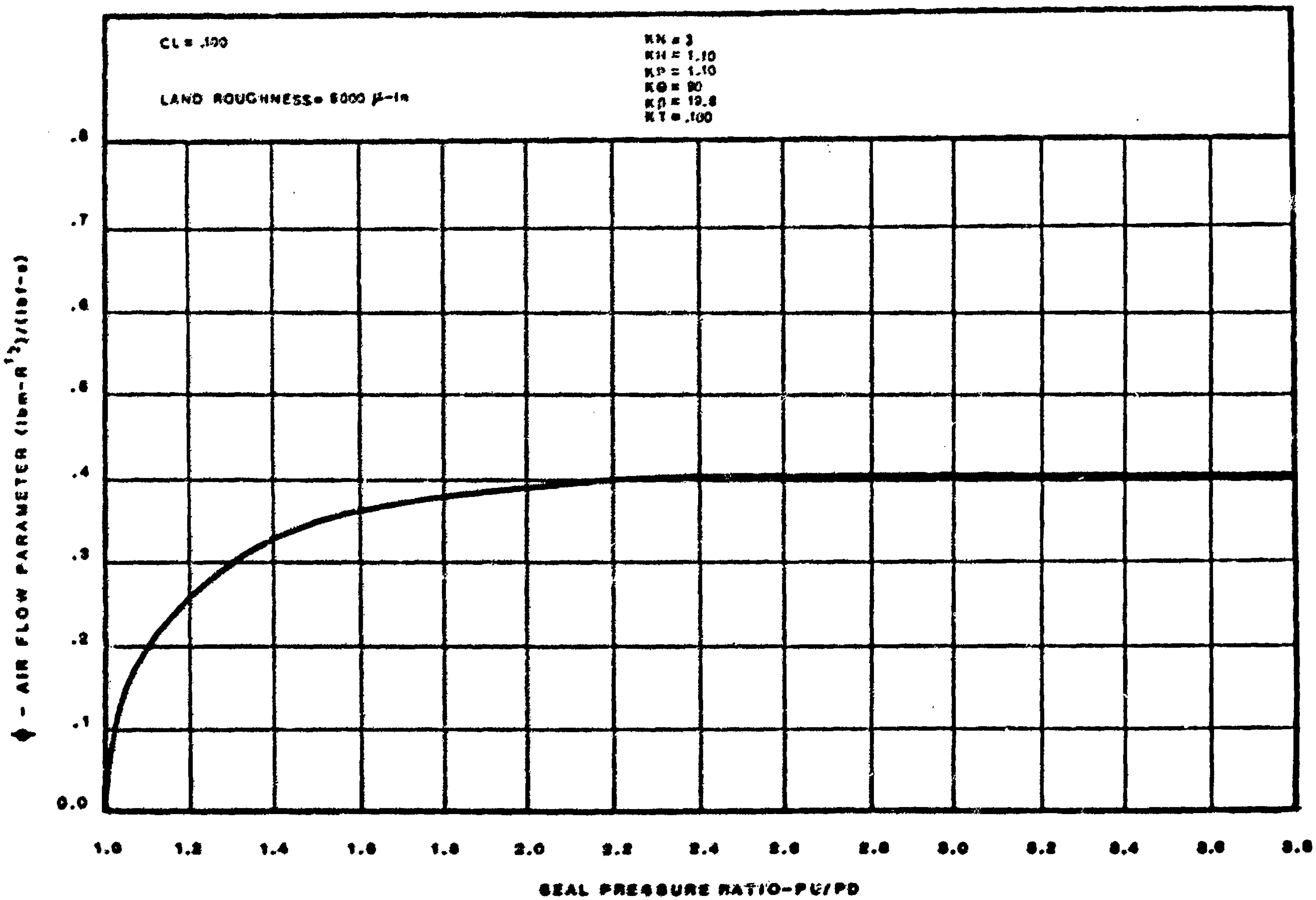
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



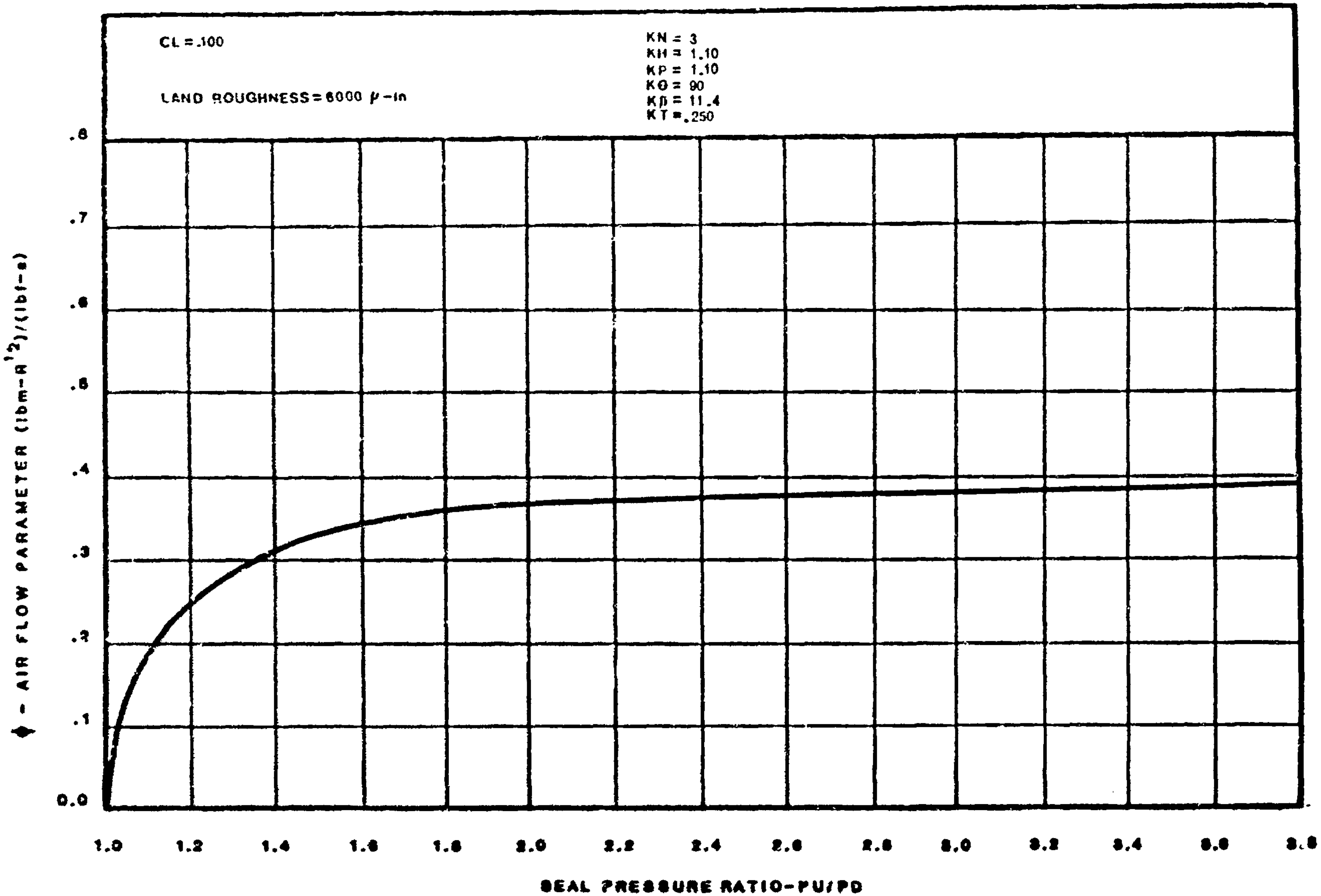
STRAIGHT SEAL

WITH SOLID- ROUGH LAND



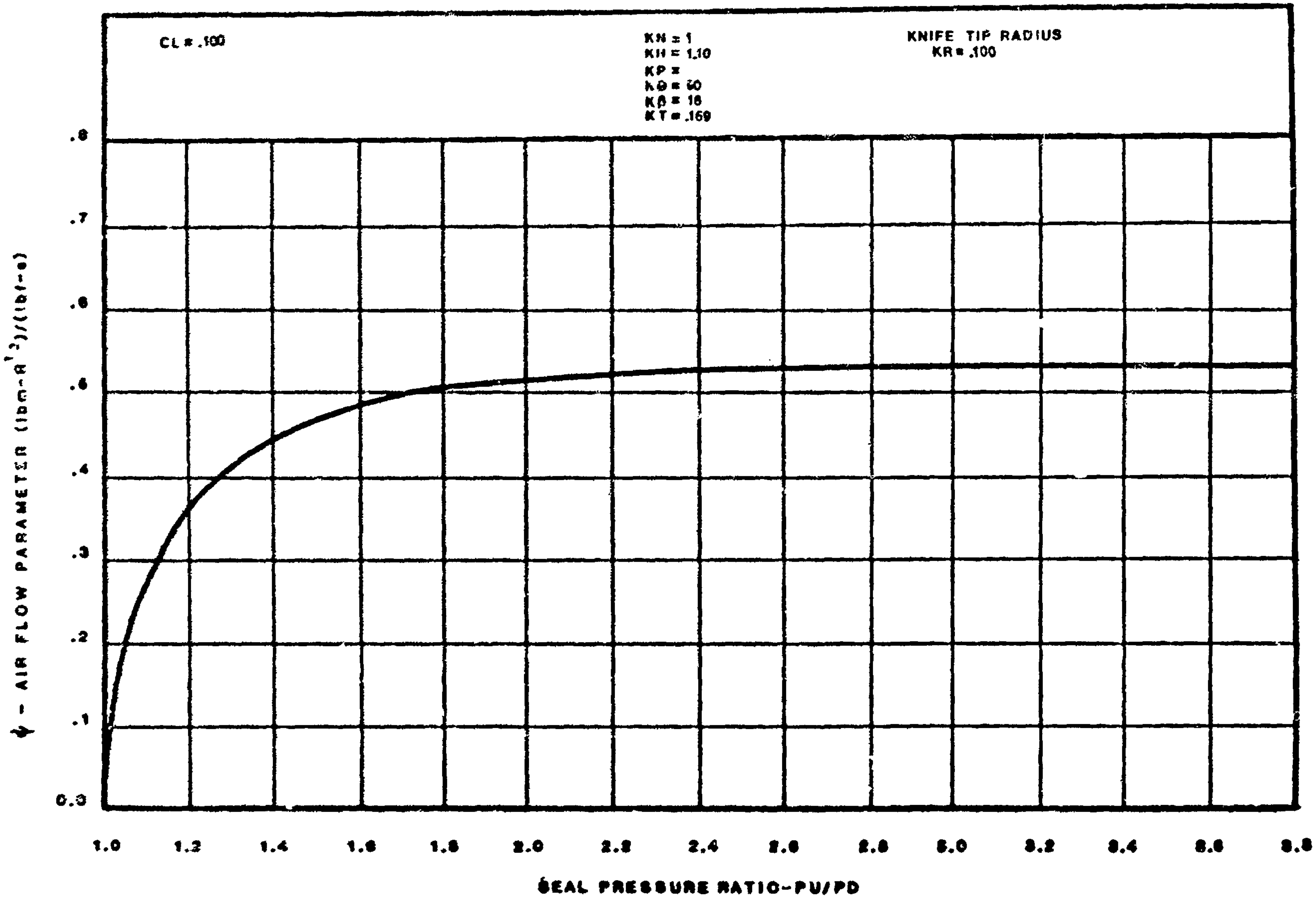
STRAIGHT SEAL

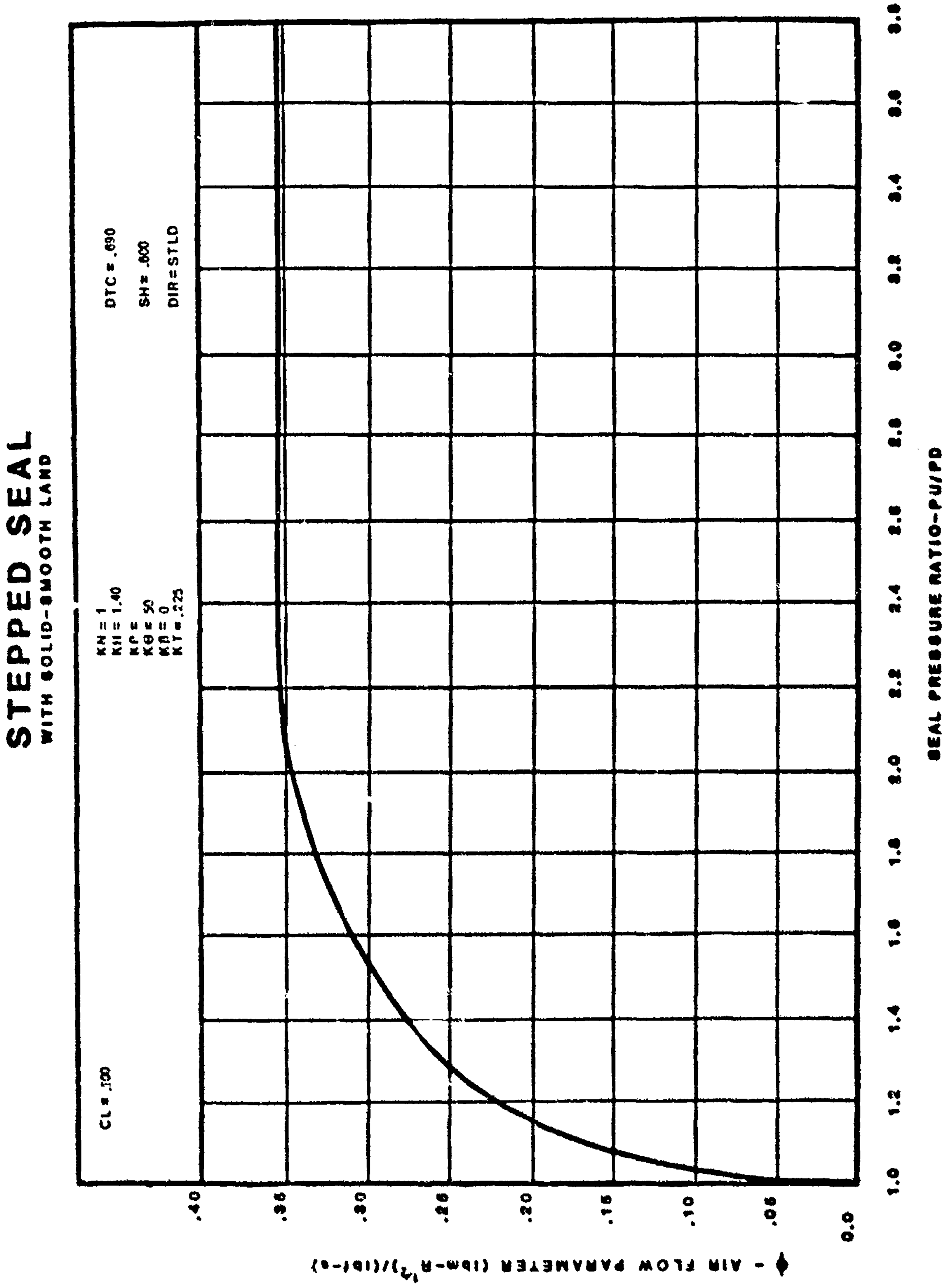
WITH SOLID- ROUGH LAND

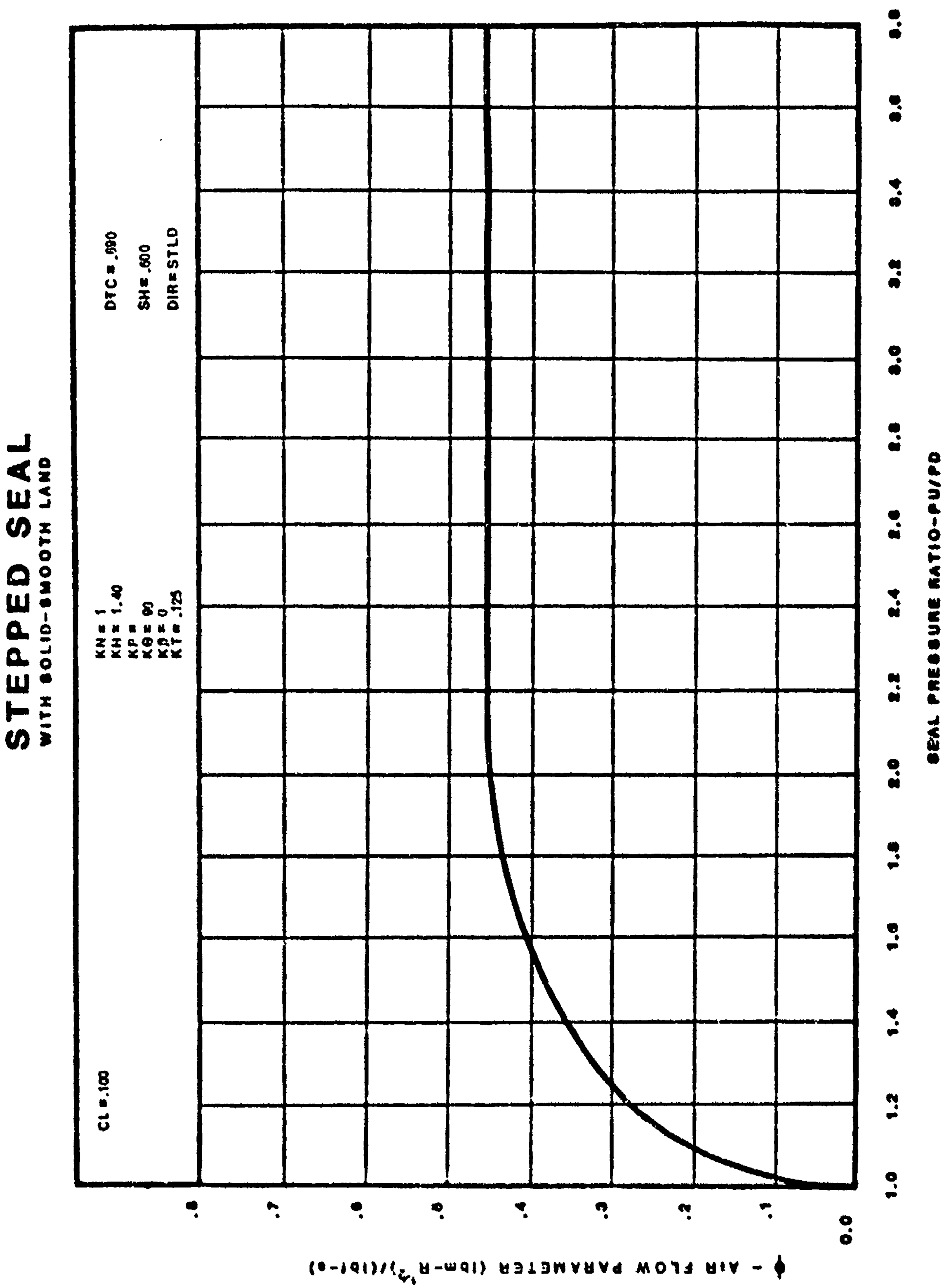


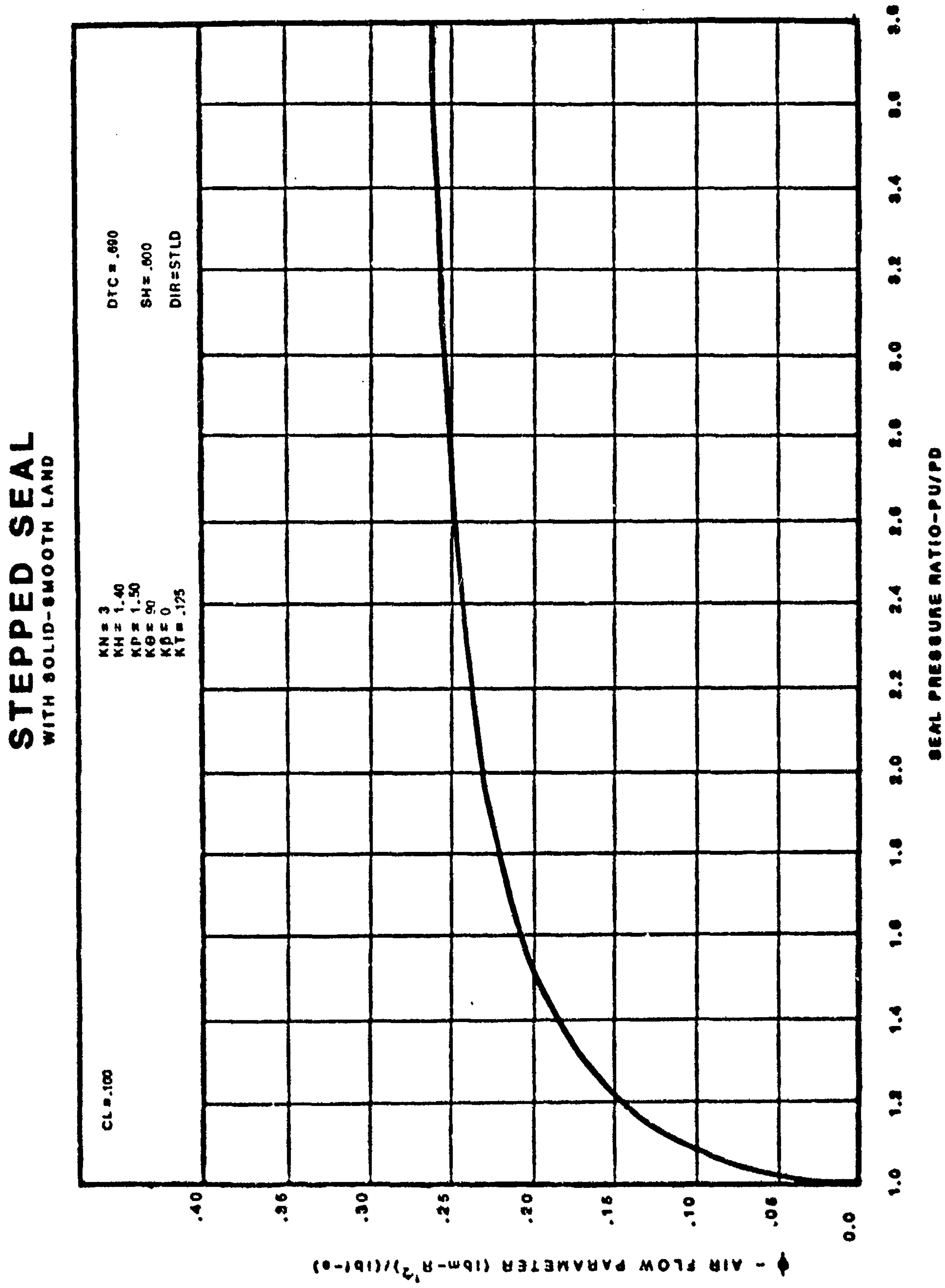
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND



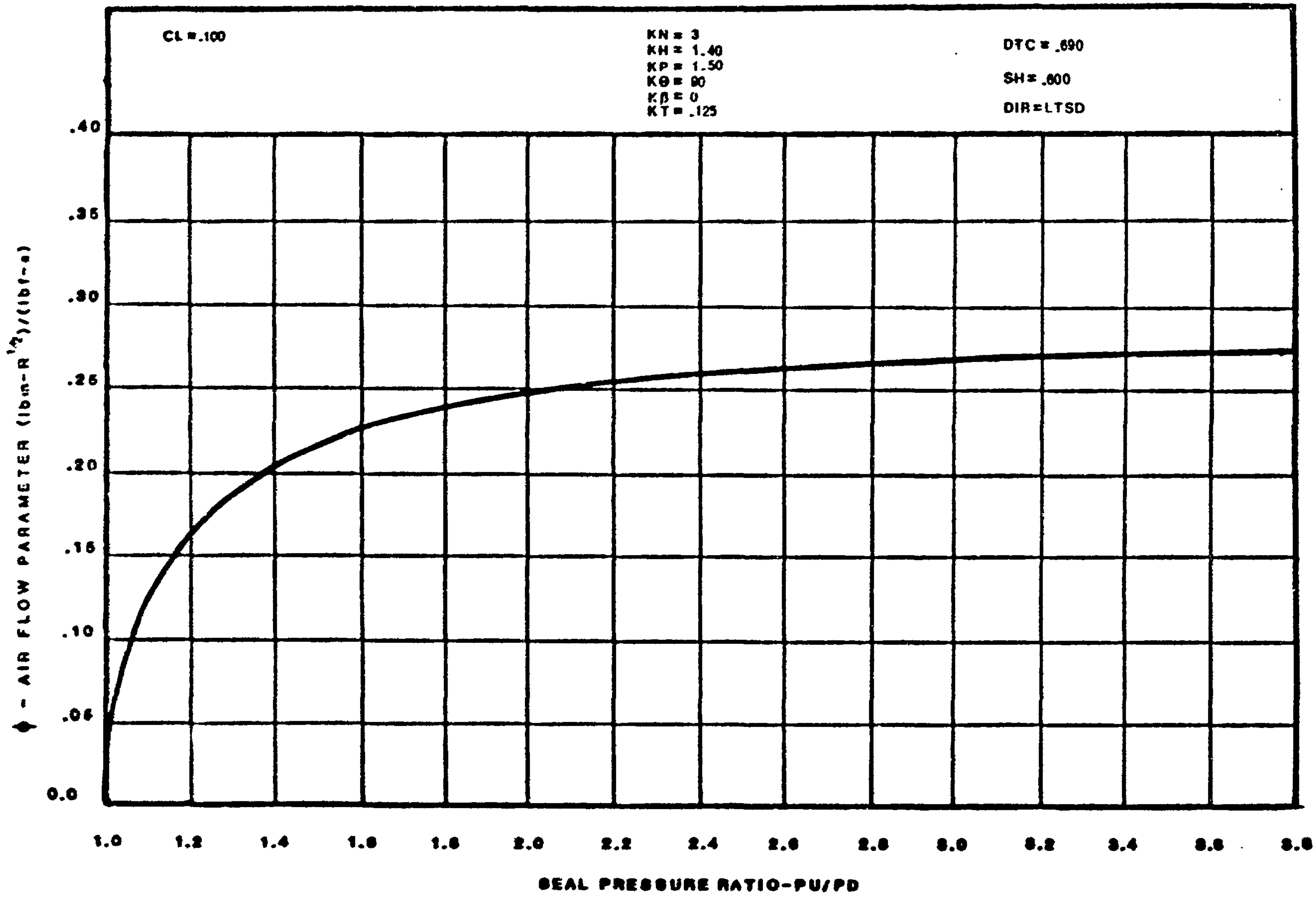

STEPPED SEAL
WITH SOLID-SMOOTH LAND
KN = 1
KII = 1.40
KP =
KΘ = 50
KB = 0
KT = .225
DTC = .690
SH = .600
DIR = STLD
CL = .100
SEAL PRESSURE RATIO-PU/PD
Φ - AIR FLOW PARAMETER (lbm-R^½)/(lbf-s)


STEPPED SEAL
WITH SOLID-SMOOTH LAND
CL=.100
KN=1
KH=1.40
KP=
KΘ=90
Kβ=0
KT=.125
DTC=.690
SH=.600
DIR=STLD
Φ - AIR FLOW PARAMETER (lbm-R^½)/(lbf-s)
SEAL PRESSURE RATIO-PU/PD
0.0
.1
.2
.3
.4
.5
.6
.7
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8


STEPPED SEAL
WITH SOLID-SMOOTH LAND
CL=.100
KN=3
KH=1.40
KP=1.50
Kθ=90
Kβ=0
KT=.125
DTC=.690
SH=.600
DIR=STLD
.40
.35
.30
.25
.20
.15
.10
.05
0.0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
SEAL PRESSURE RATIO-PU/PD
ϕ - AIR FLOW PARAMETER (lbm-°R½)/(lbf-s)

STEPPED SEAL

WITH SOLID-SMOOTH LAND



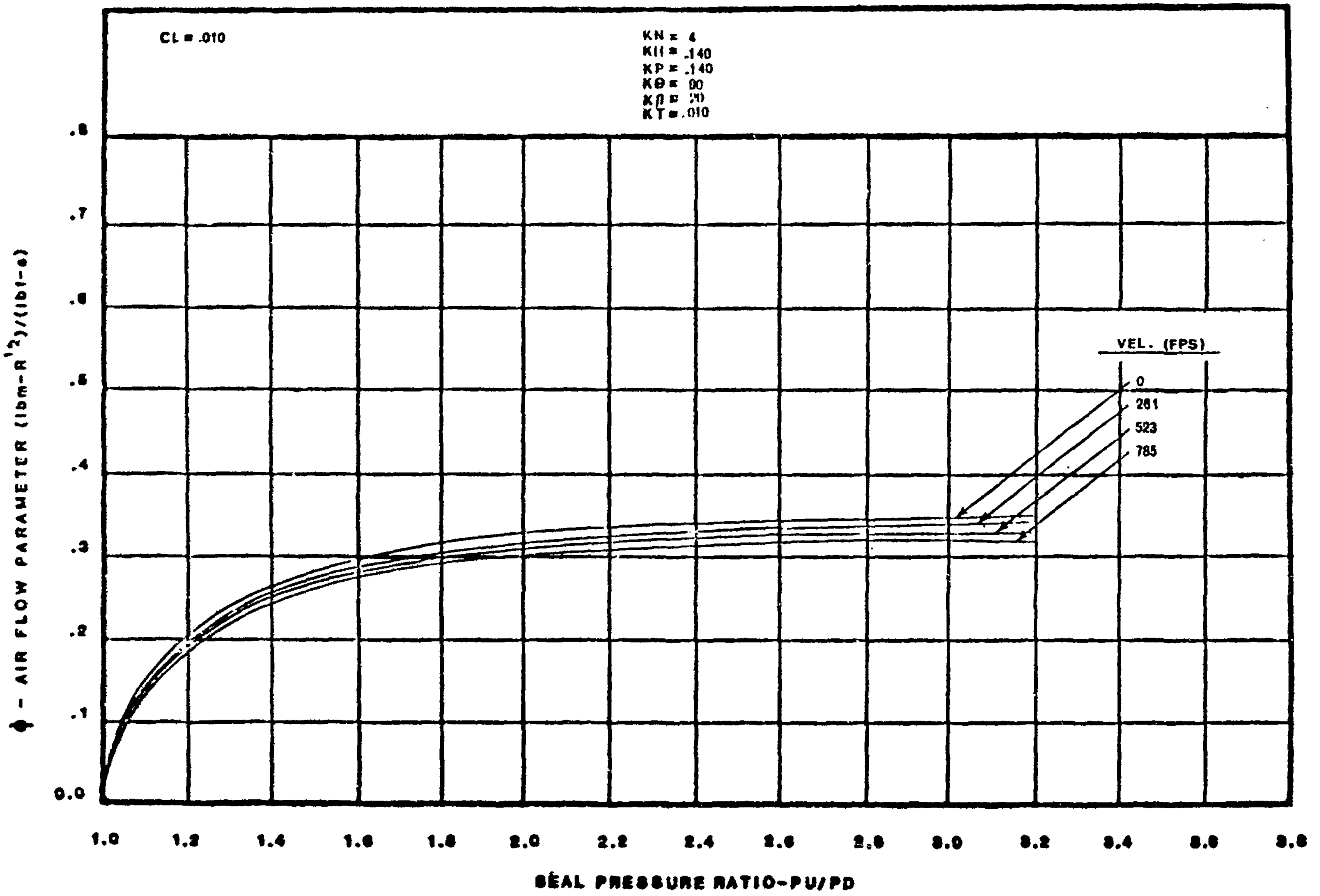
B.2 3-D RIG DATA

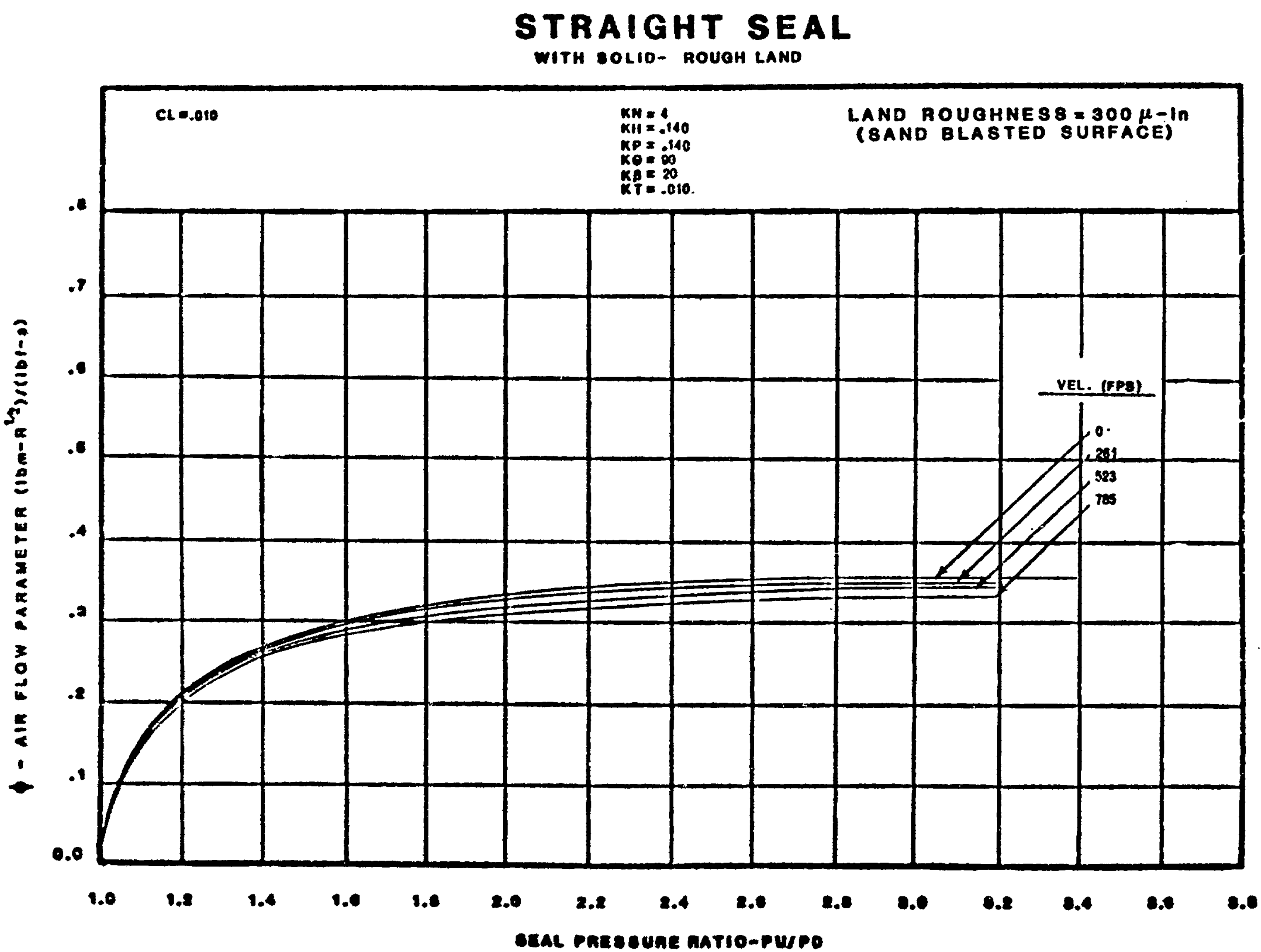
The static and dynamic performance data acquired from the 3-D rig tests on full-scale seals:

- o Supported the Design Model development with data base performance and interknife cavity pressures.
- o Validated the Design Model accuracy for a seal configuration not in the development data base.

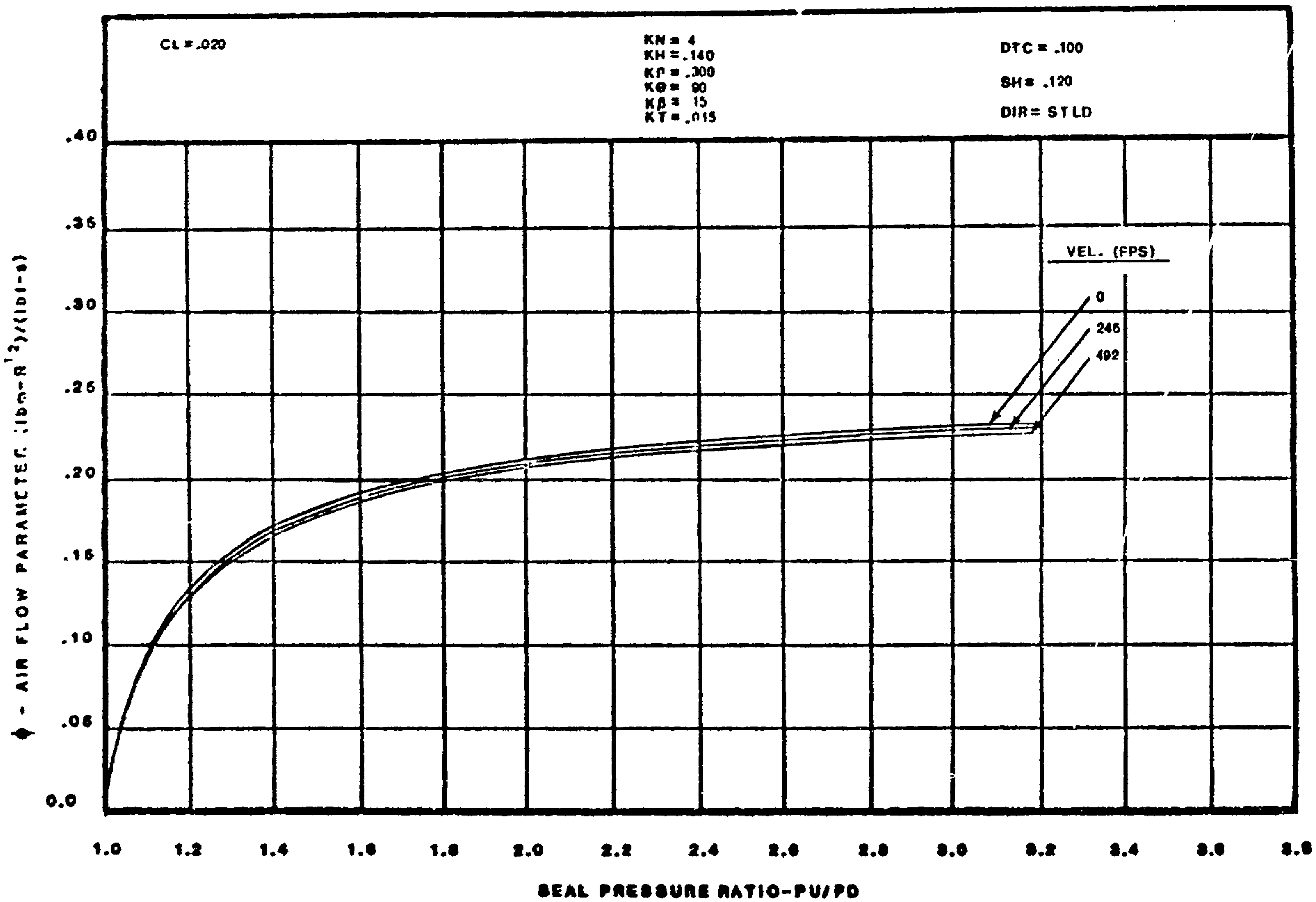
STRAIGHT SEAL

WITH SOLID-SMOOTH LAND




STRAIGHT SEAL
WITH SOLID- ROUGH LAND
CL=.010
KN=4
KH=.140
KP=.140
KΘ=90
Kβ=20
KT=.010
LAND ROUGHNESS = 300 μ-in
(SAND BLASTED SURFACE)
VEL. (FPS)
0
261
523
785
.8
.7
.6
.5
.4
.3
.2
.1
0.0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
SEAL PRESSURE RATIO-PU/PD
ϕ - AIR FLOW PARAMETER (lbm-R^1/2)/(lbf-s)

STEPPED SEAL
WITH SOLID-SMOOTH LAND



APPENDIX C

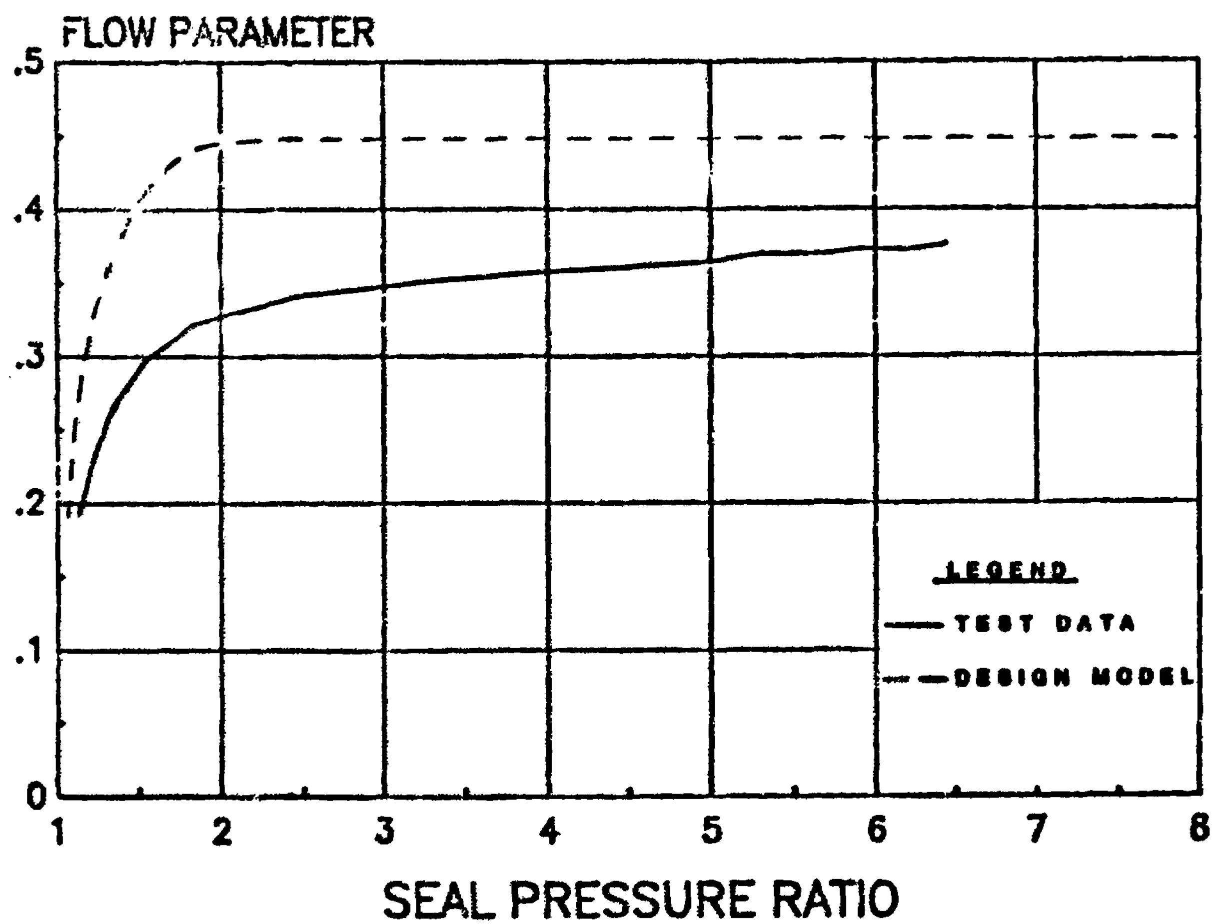
EFFECT OF THE INTERKNIFE CAVITY ASPECT RATIO (KP/KH) ON STRAIGHT SEAL PERFORMANCE

The following static data were acquired in the 2-D labyrinth seal test rig with a pressurized inlet plenum and an atmospheric exhaust. The inlet air temperatures were the same as the rig ambient air.

The data reduction and plotting were automated. Irregular plots of the seal performance are the result of the plot algorithm. The test points are connected with straight lines without regard for smoothing data scatter.

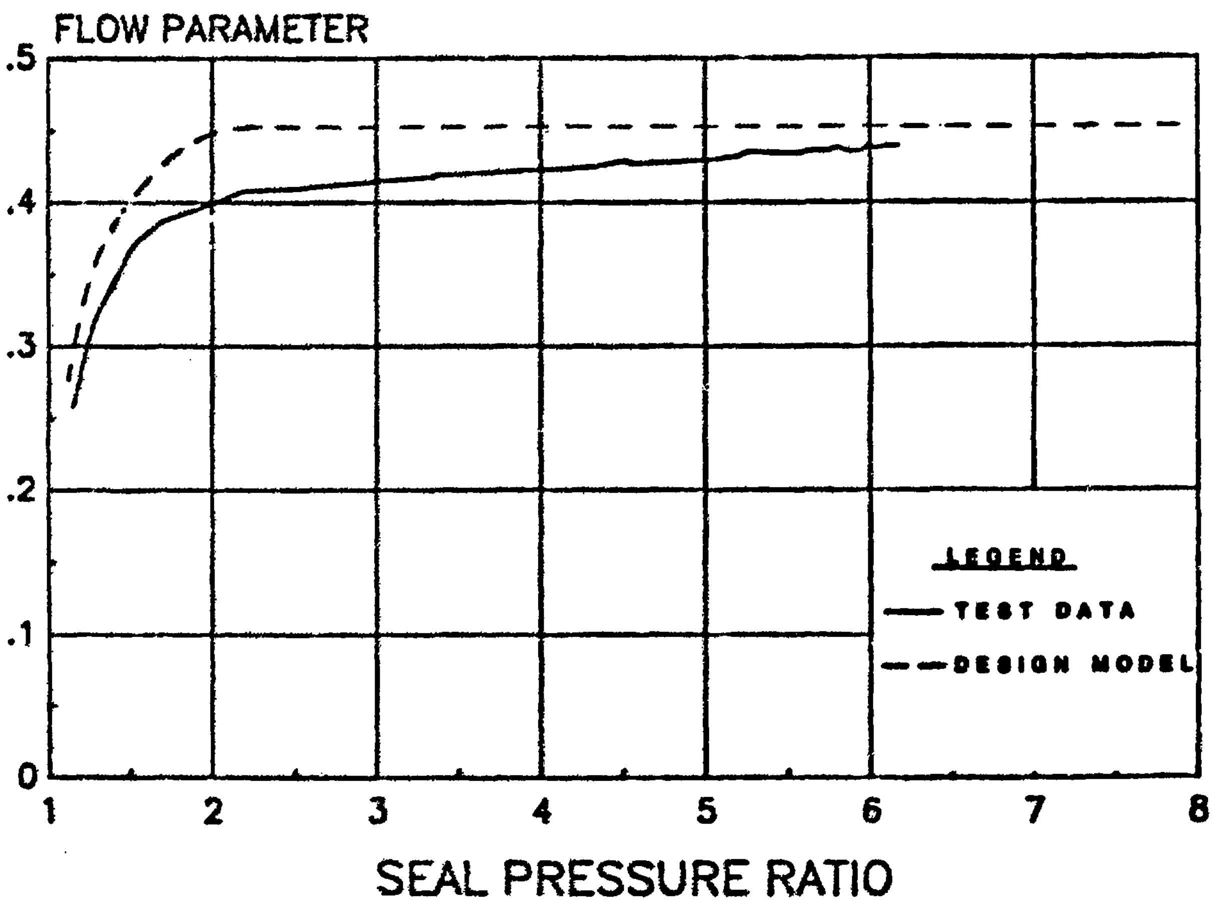
TEST 1 VERTICAL 2–KNIFE STRAIGHT SEAL KP/KH=0.40, KP/CL=8.8

CL=.005

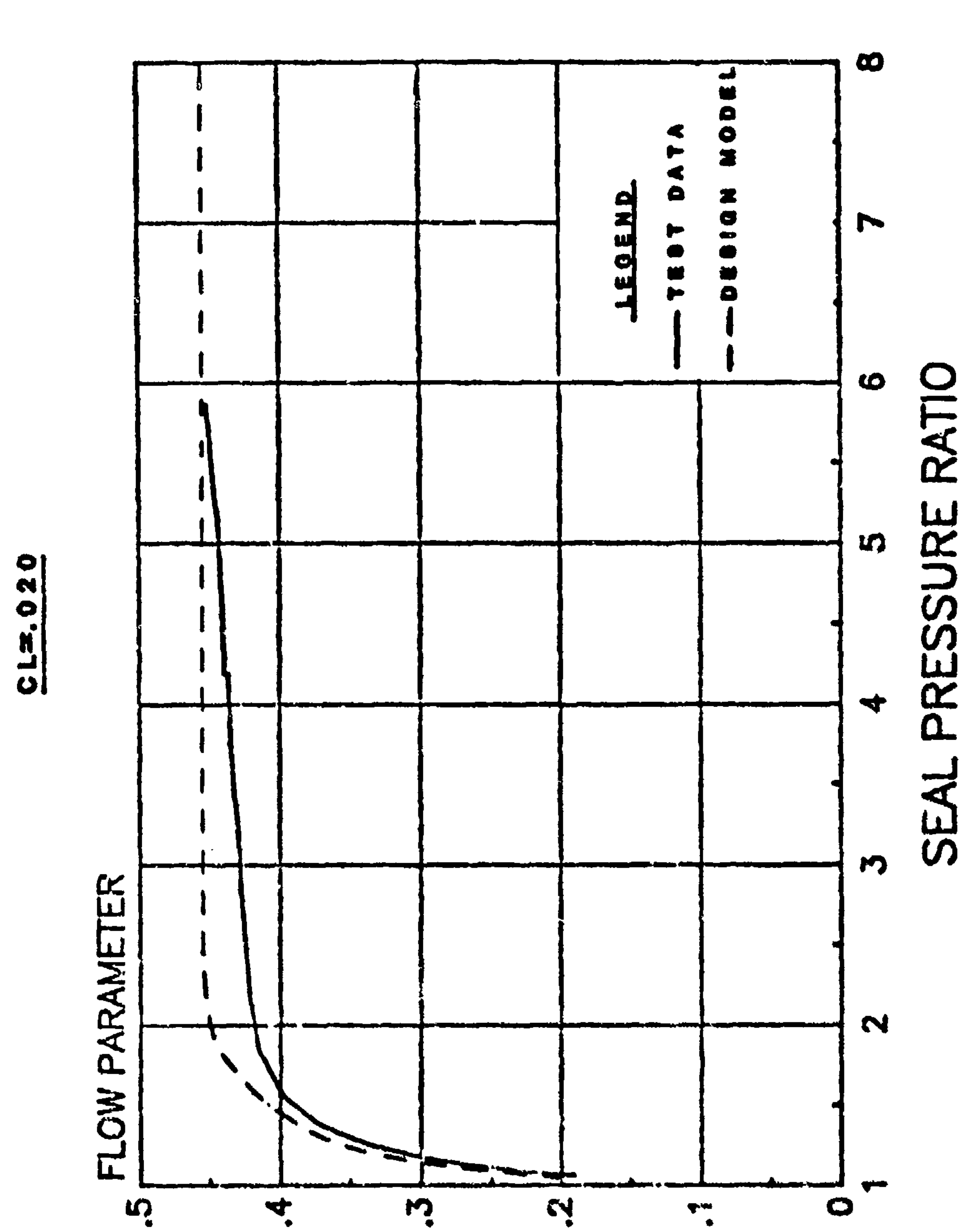


TEST 2 VERTICAL 2-KNIFE STRAIGHT SEAL KP/KH=0.40, KP/CL= 4.4

CL=.010

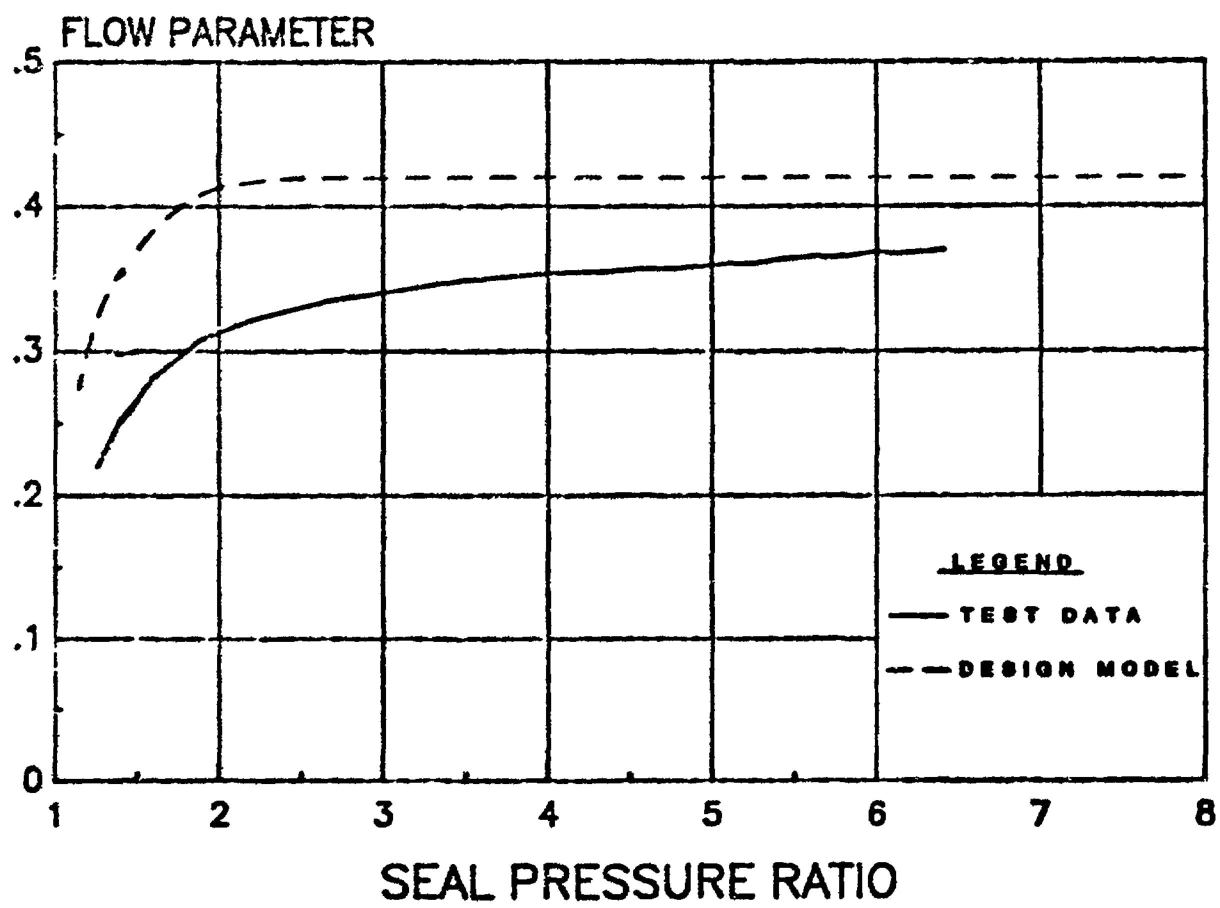


TEST 3 VERTICAL 2–KNIFE STRAIGHT SEAL KP/KH=0.40, KP/CL= 2.2

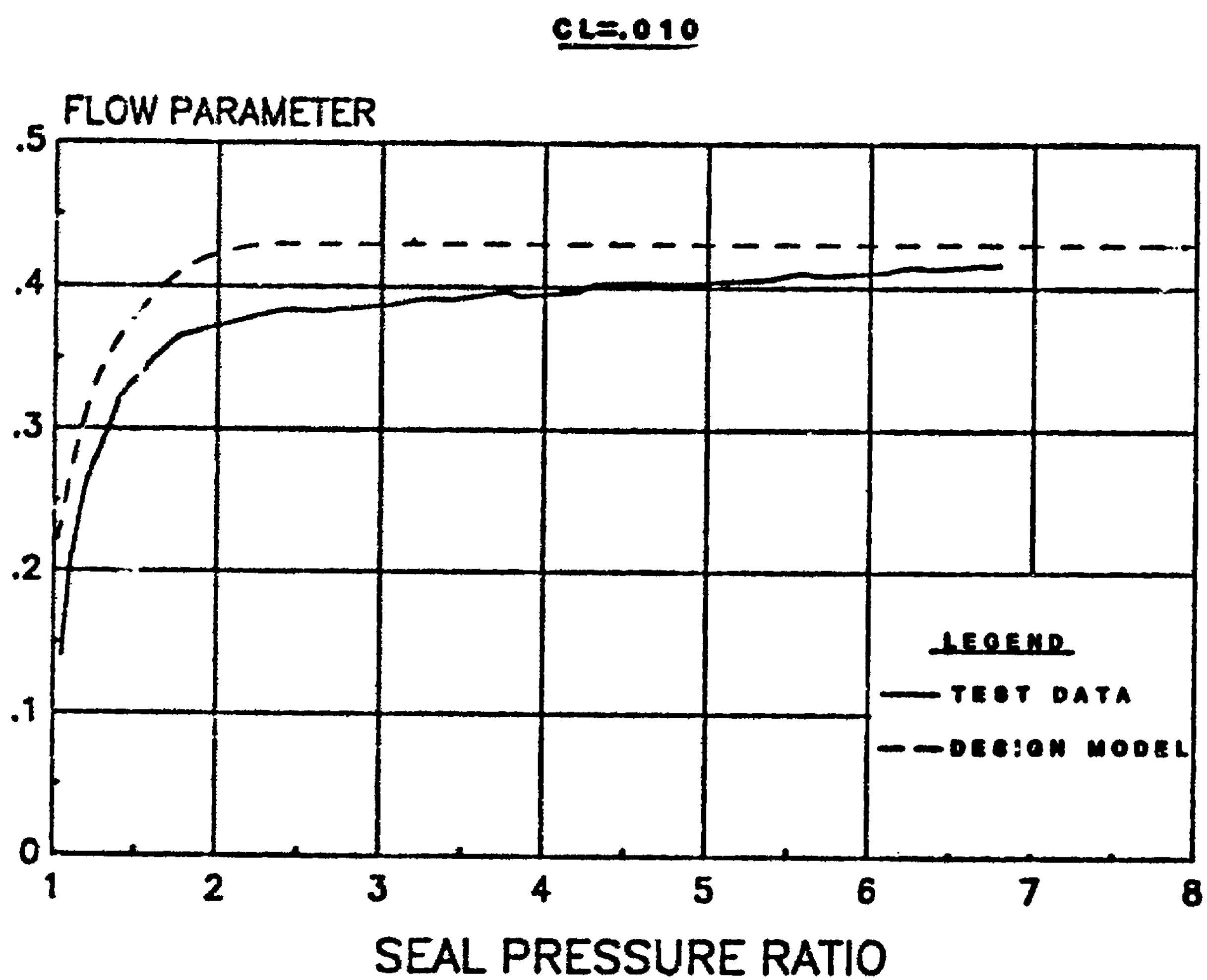


TEST 4 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=0.40, KP/CL=8.8

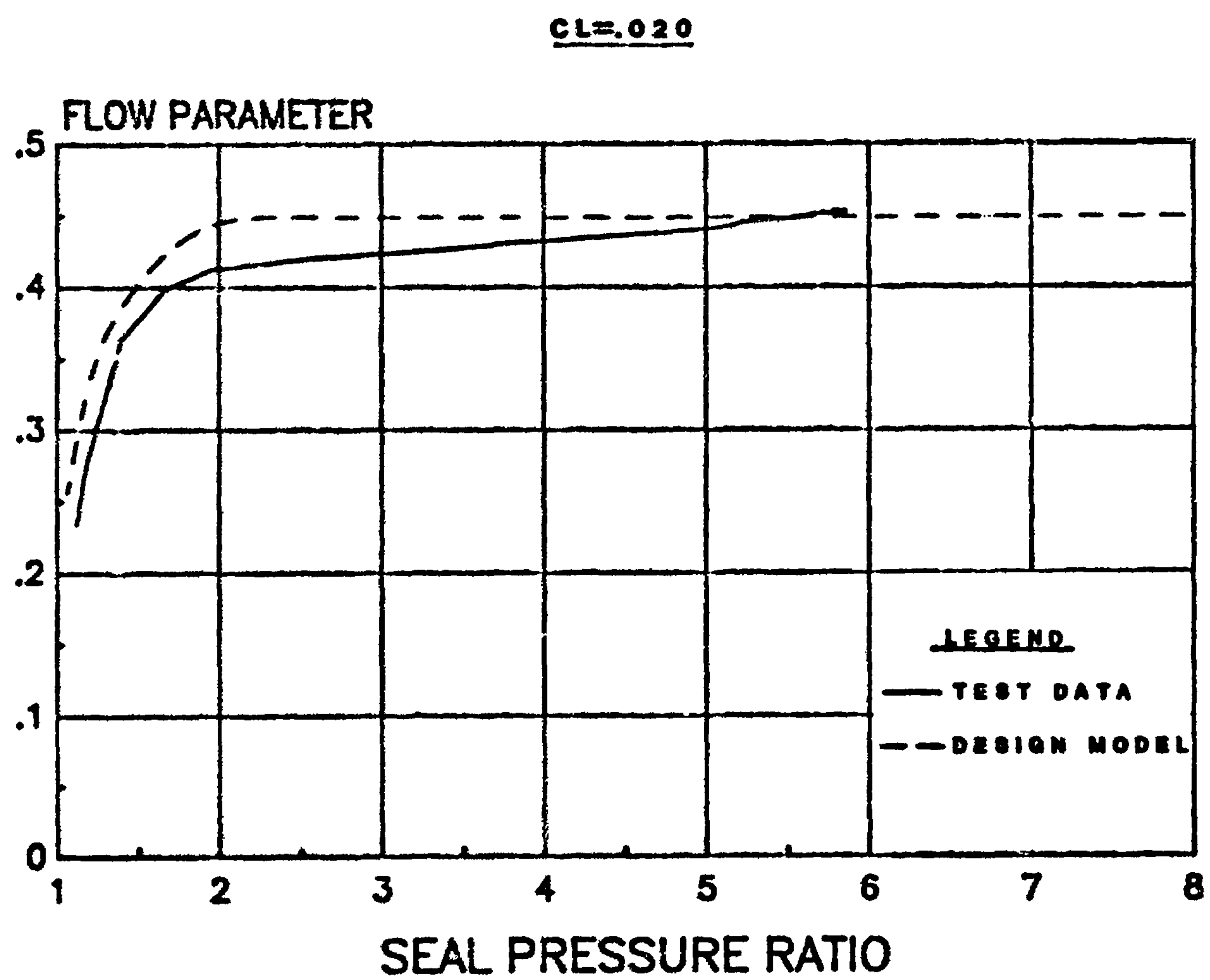
CL=.005



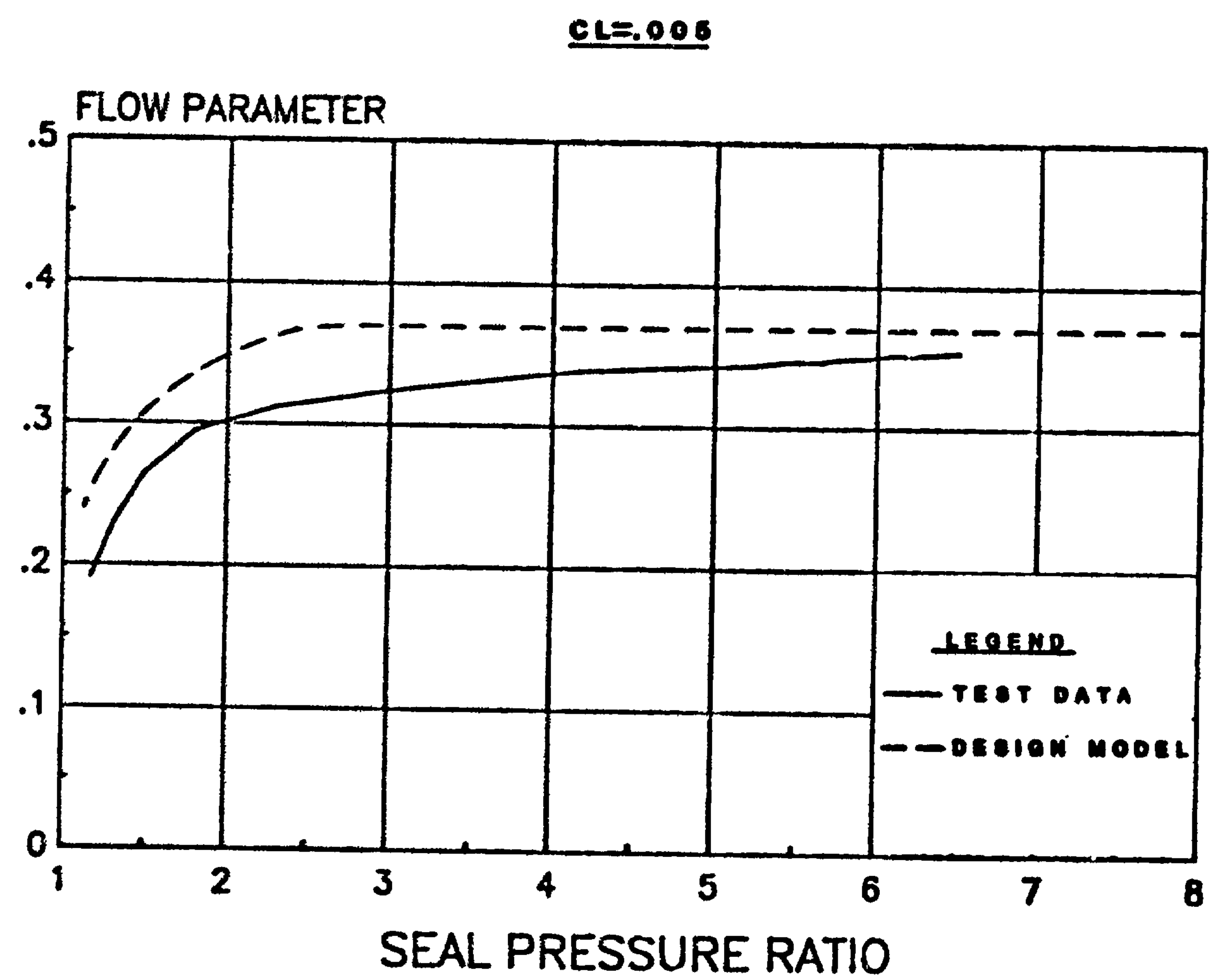
TEST 5 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=0.40, KP/CL=4.4



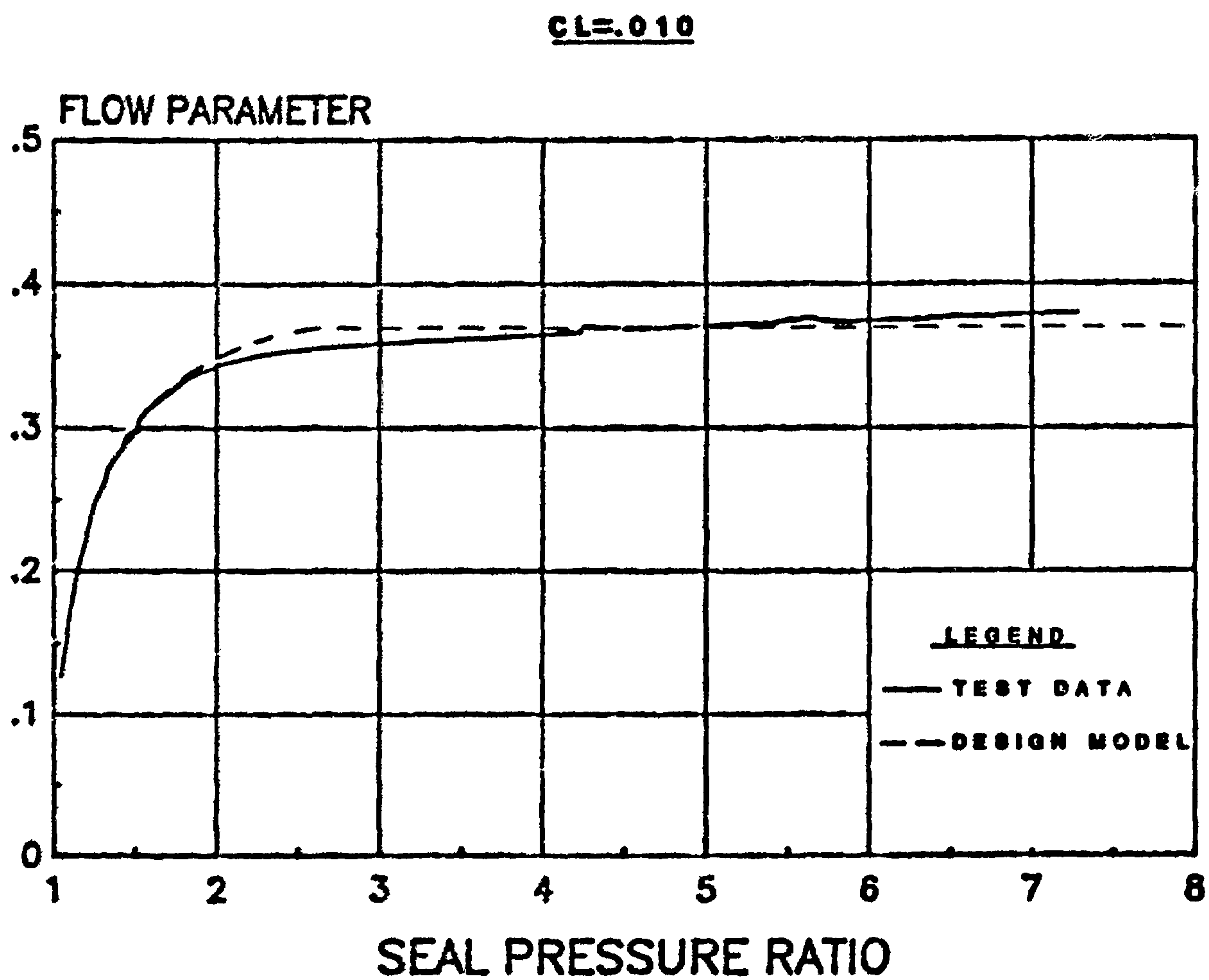
TEST 6 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=0.40, KP/CL= 2.2



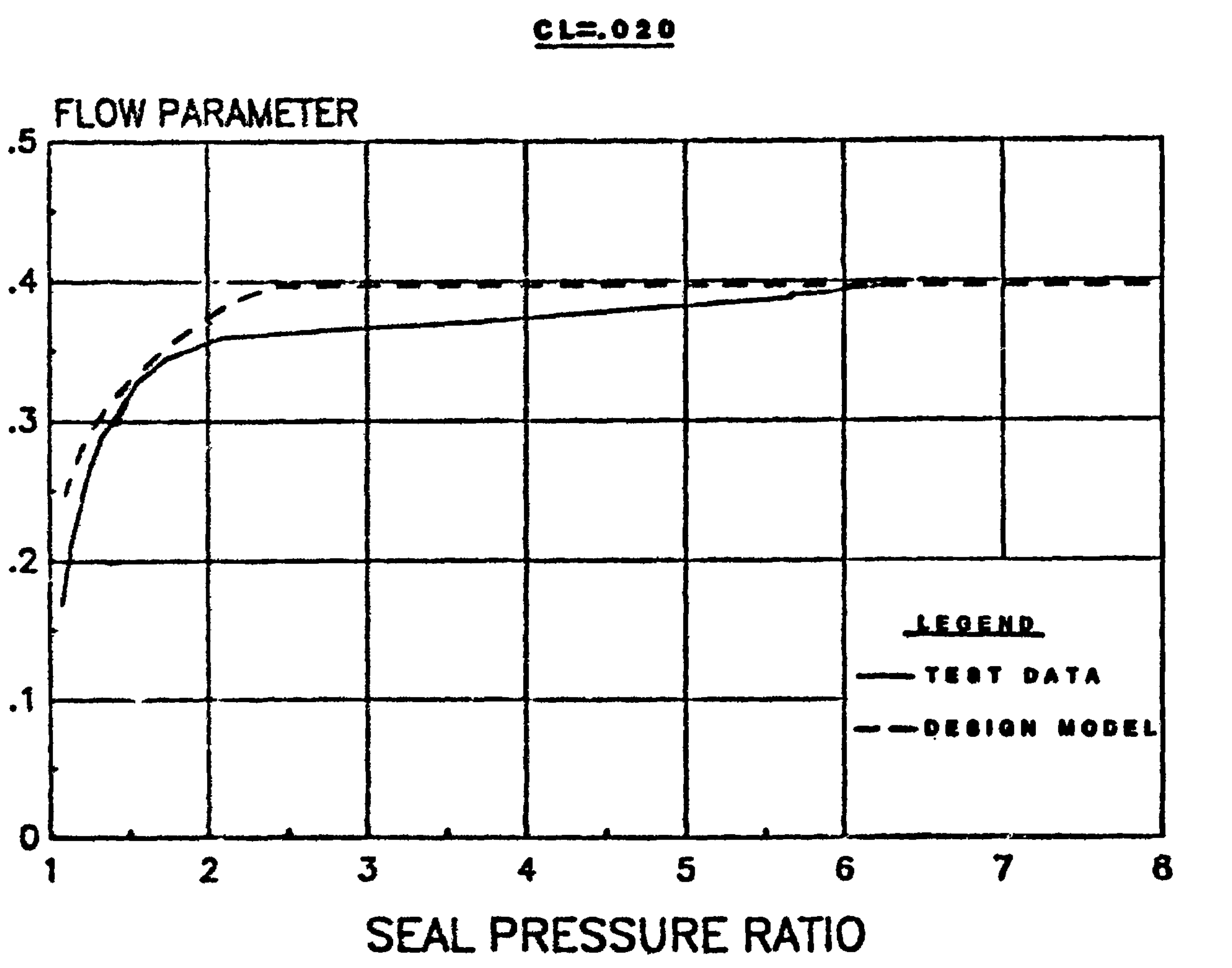
TEST 7 VERTICAL 2–KNIFE STRAIGHT SEAL KP/KH=2.00, KP/CL=44.0



TEST 8 **VERTICAL 2–KNIFE STRAIGHT SEAL KP/KH=2.00, KP/CL=22.0**

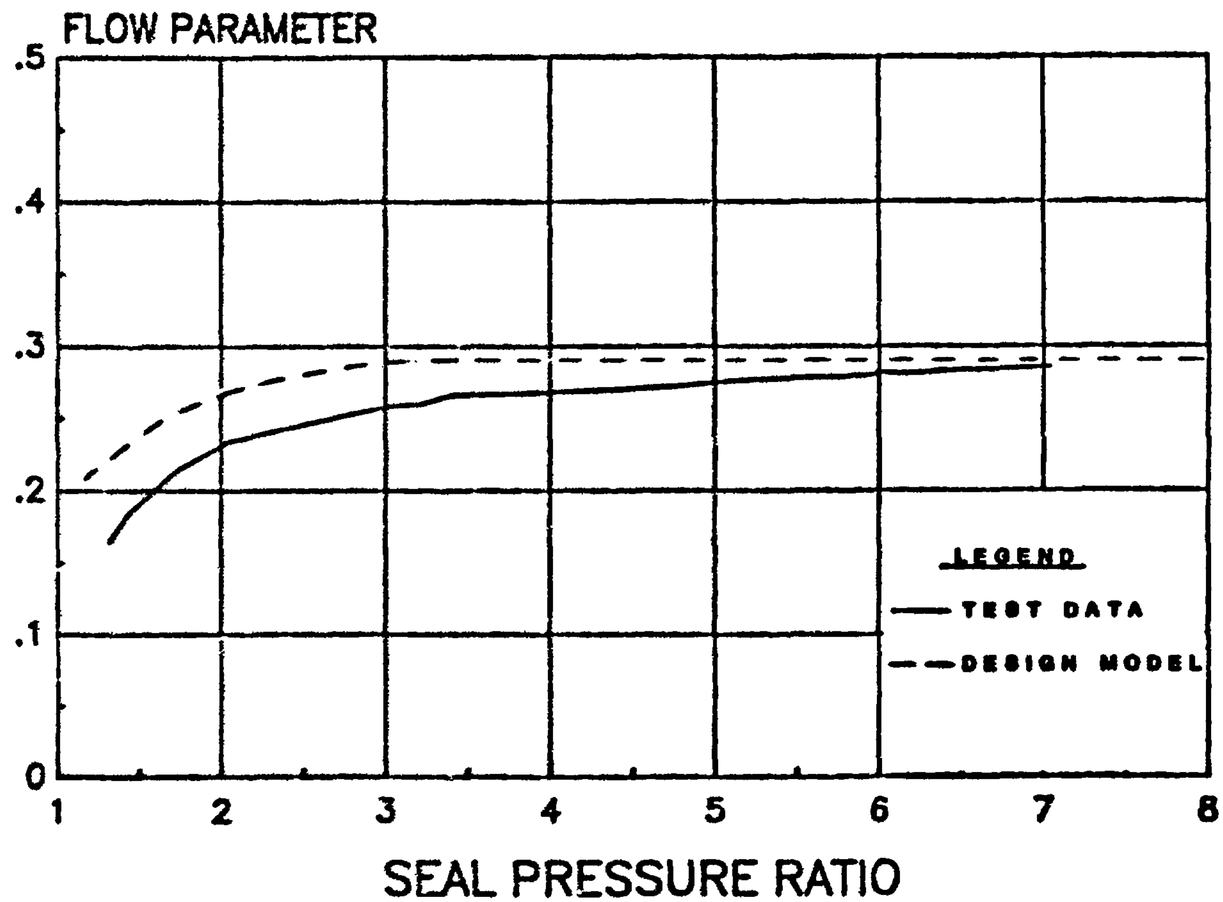


TEST 9 VERTICAL 2-KNIFE STRAIGHT SEAL KP/KH=2.00, KP/CL=11.0



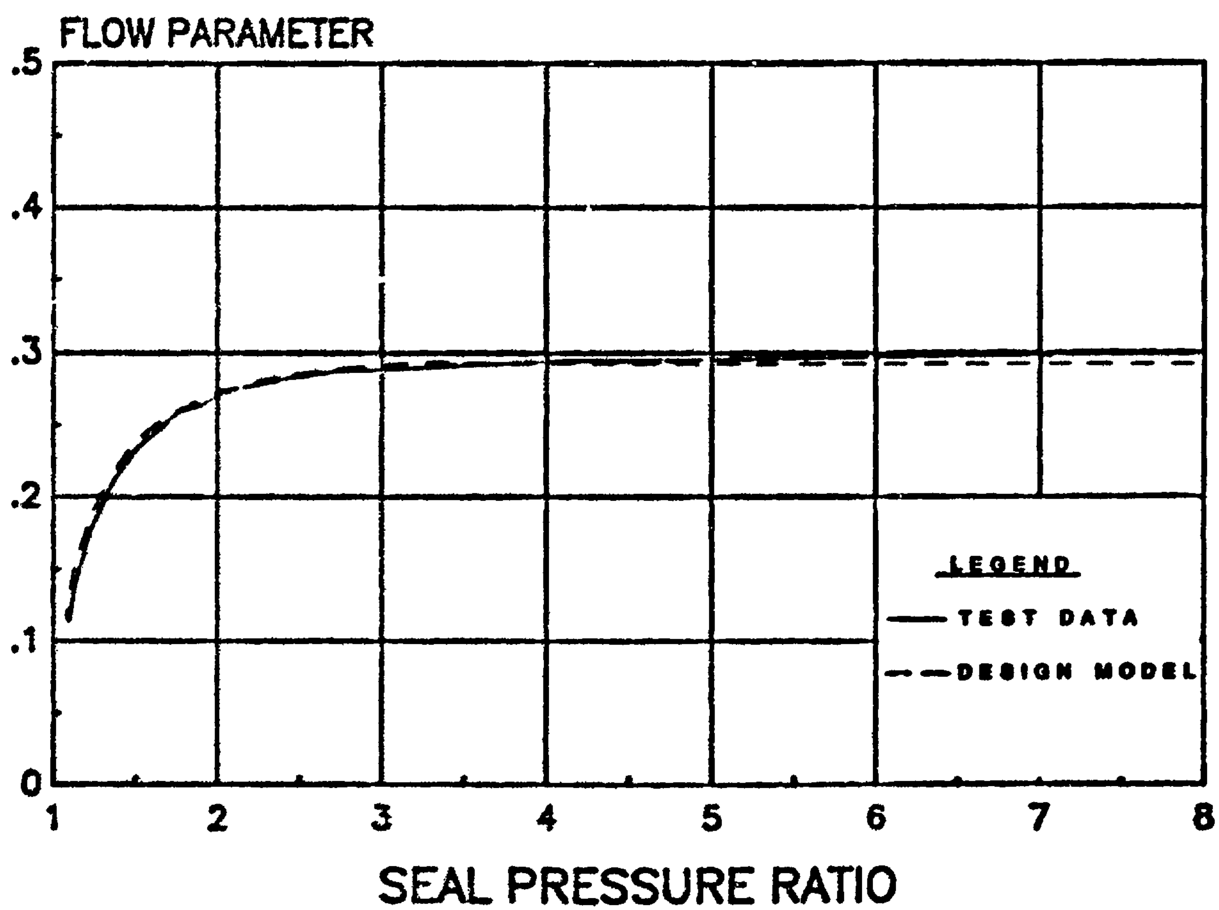
TEST 10 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=2.00, KP/CL=44.0

CL=.006

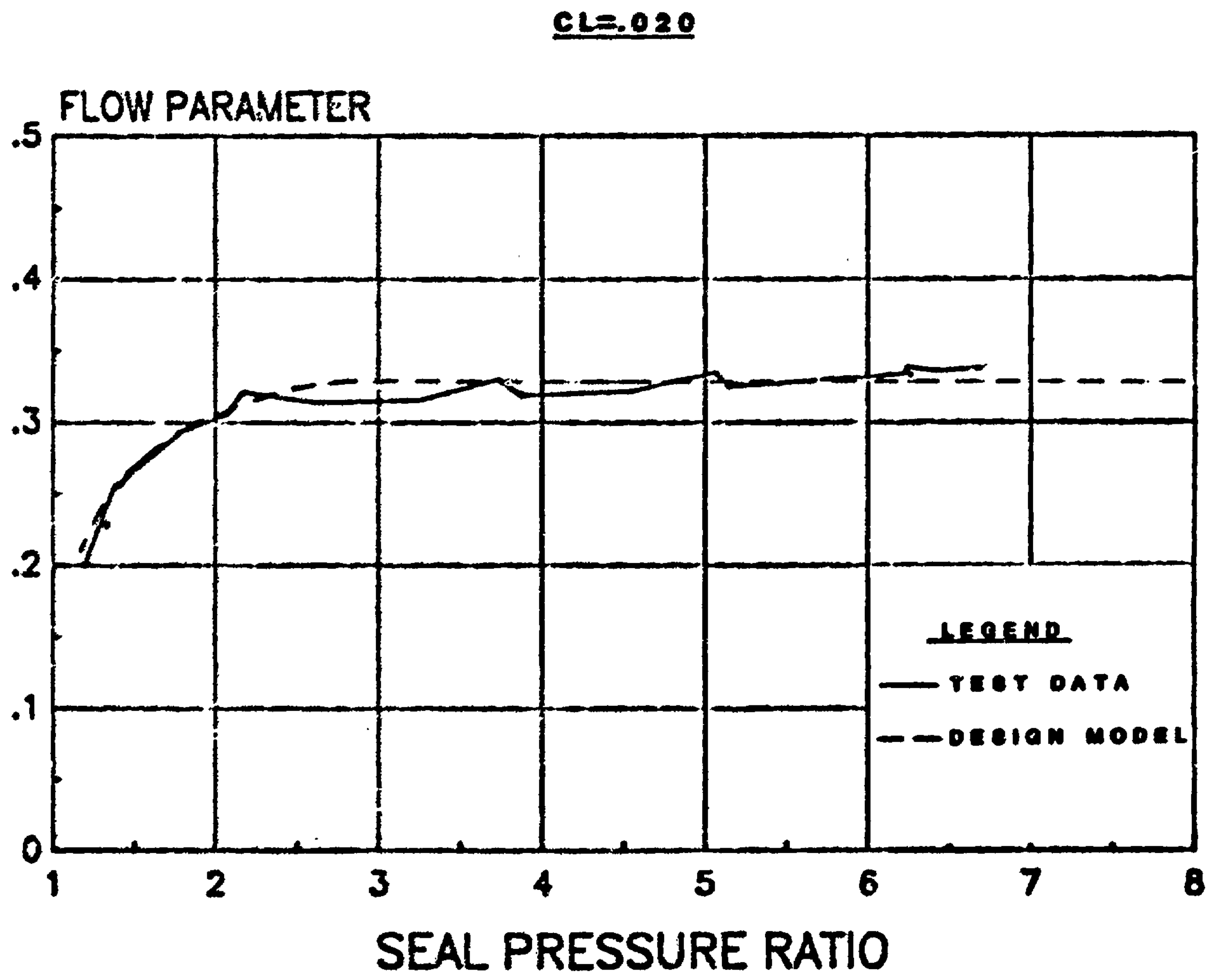


TEST 11: VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=2.00, KP/CL=22.0

CL=.010

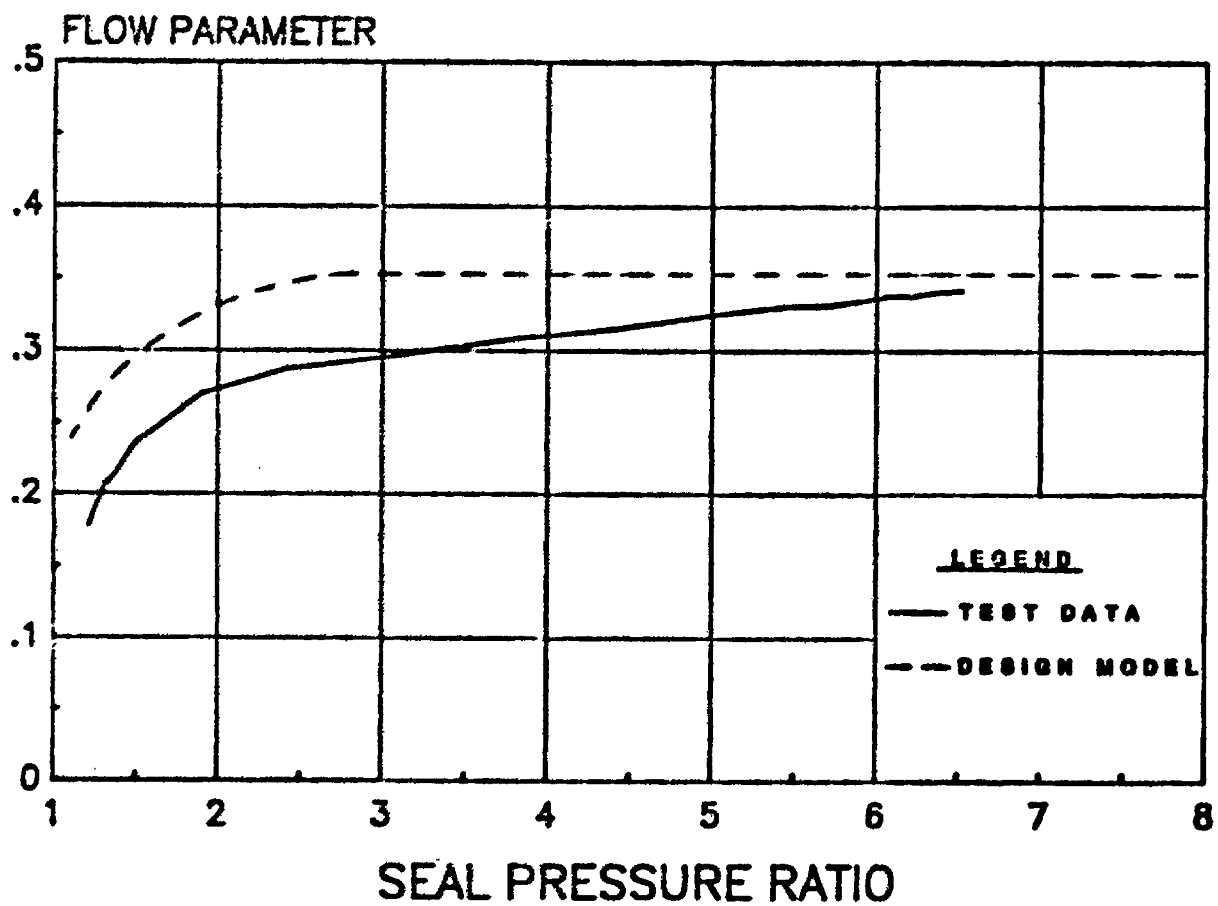


TEST 12 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=2.00, KP/CL=11.0



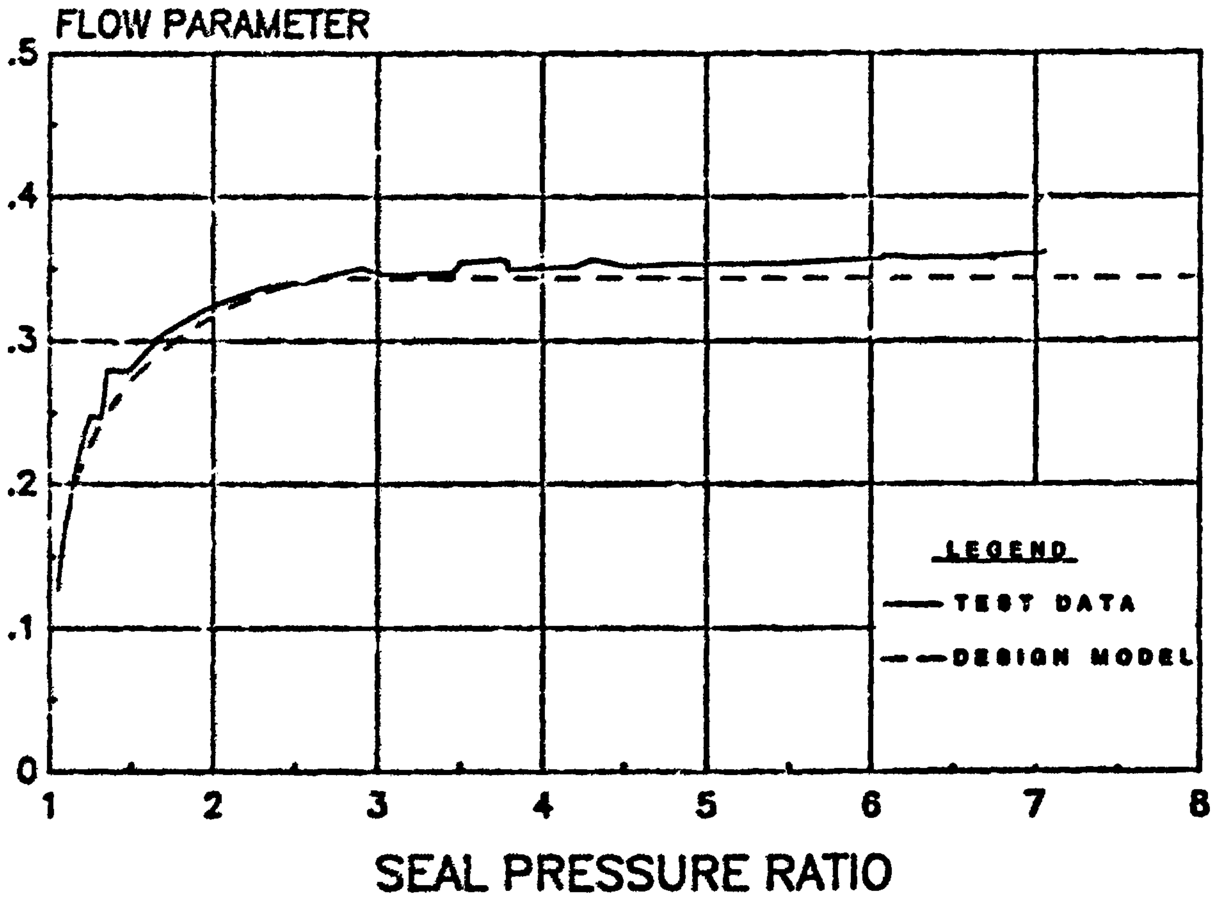
TEST 13 VERTICAL 2–KNIFE STRAIGHT SEAL KP/KH=4.00, KP/CL=88.0

CL=.005



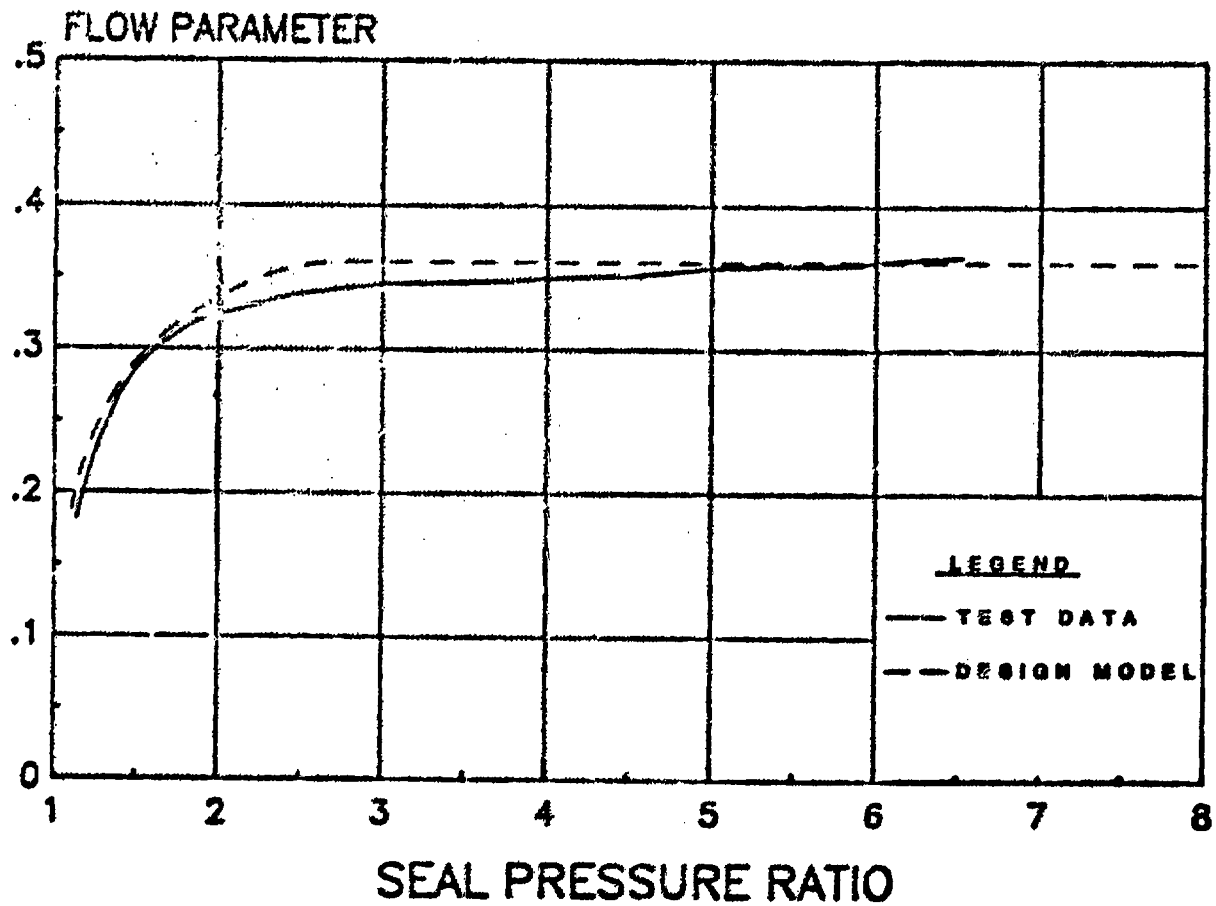
TEST 14 VERTICAL 2-KNIFE STRAIGHT SEAL KP/KH=4.00, KP/CL=44.0

CL=.010



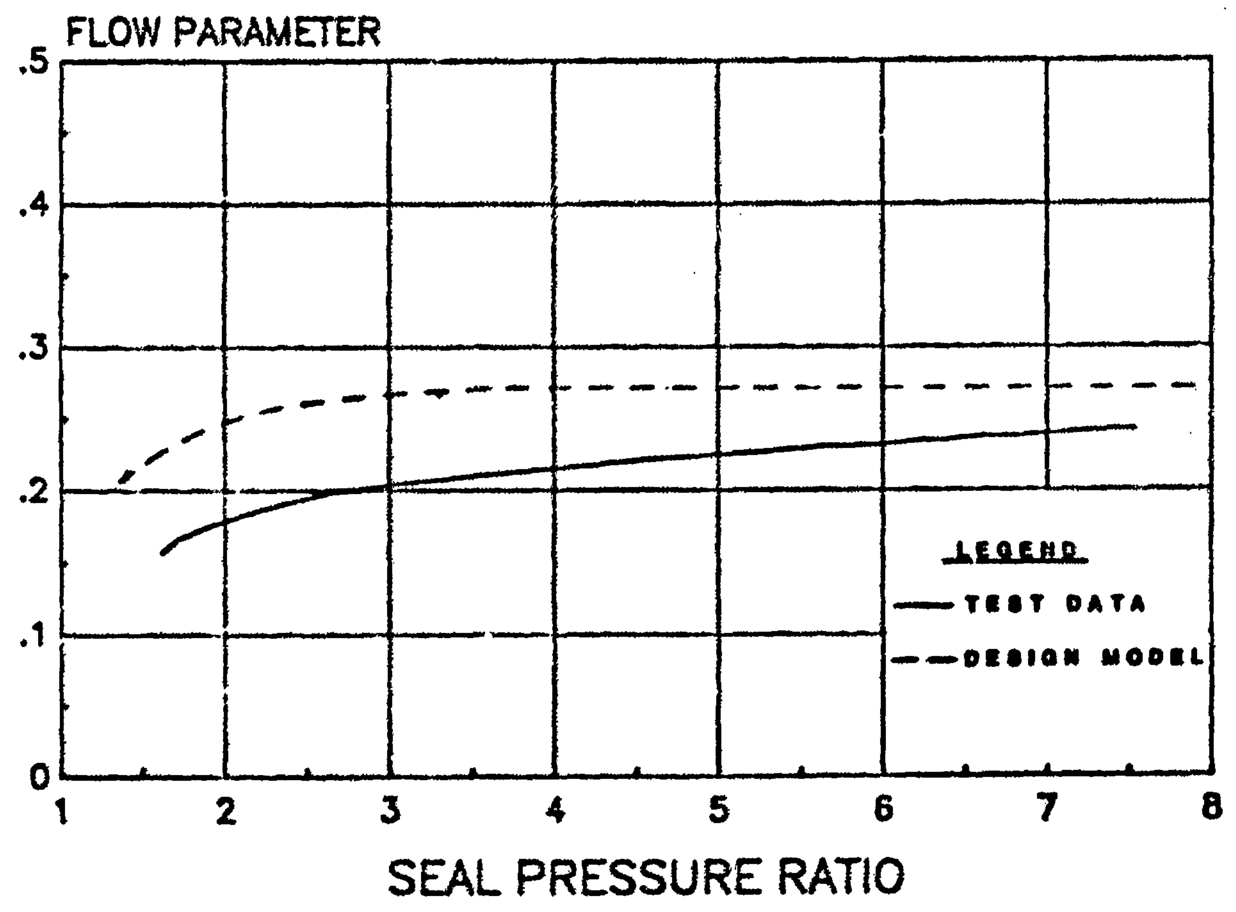
A TEST 15 VERTICAL 2-KNIFE STRAIGHT SEAL KP/KH=4.00, KP/CL=22.0

CL=.020



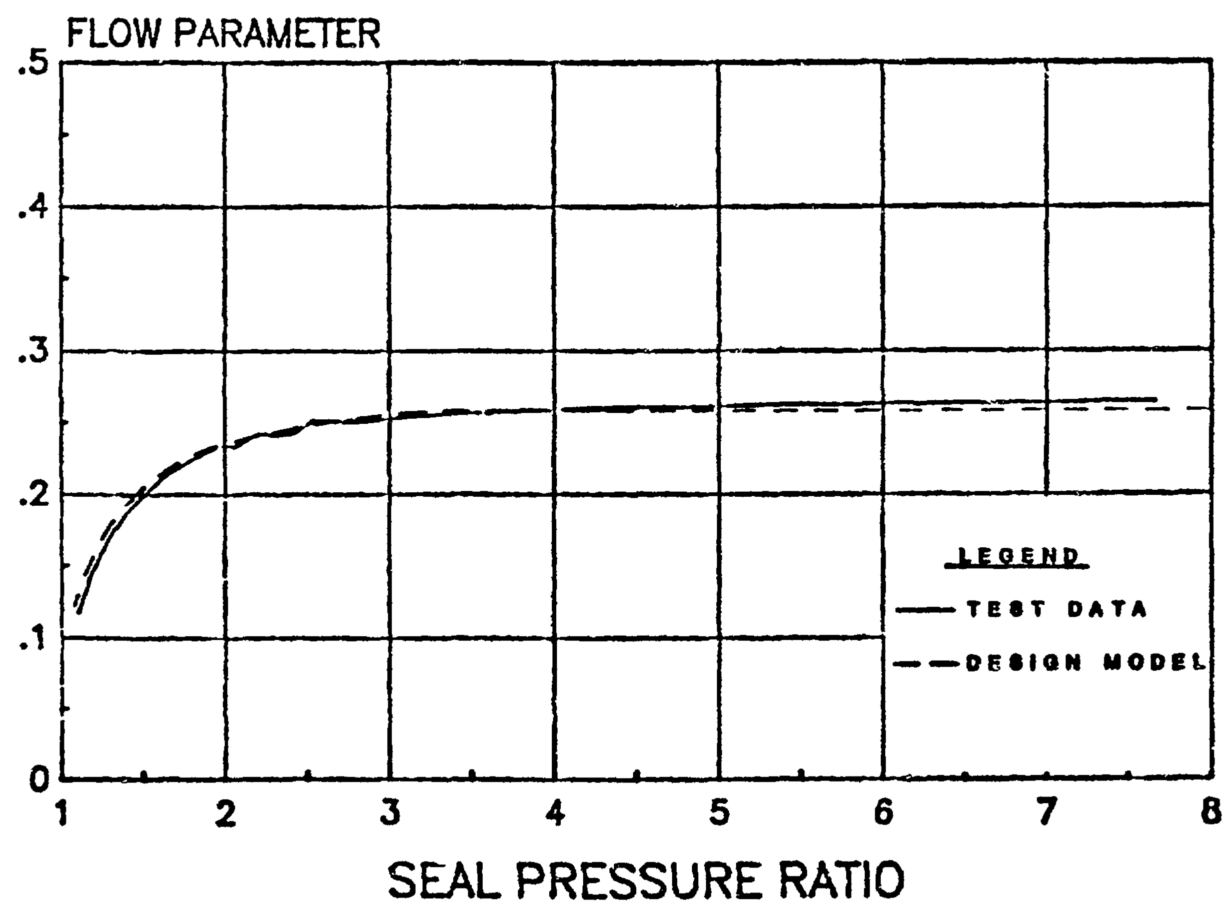
TEST 16 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=4.00, KP/CL=88.0

CL=.006



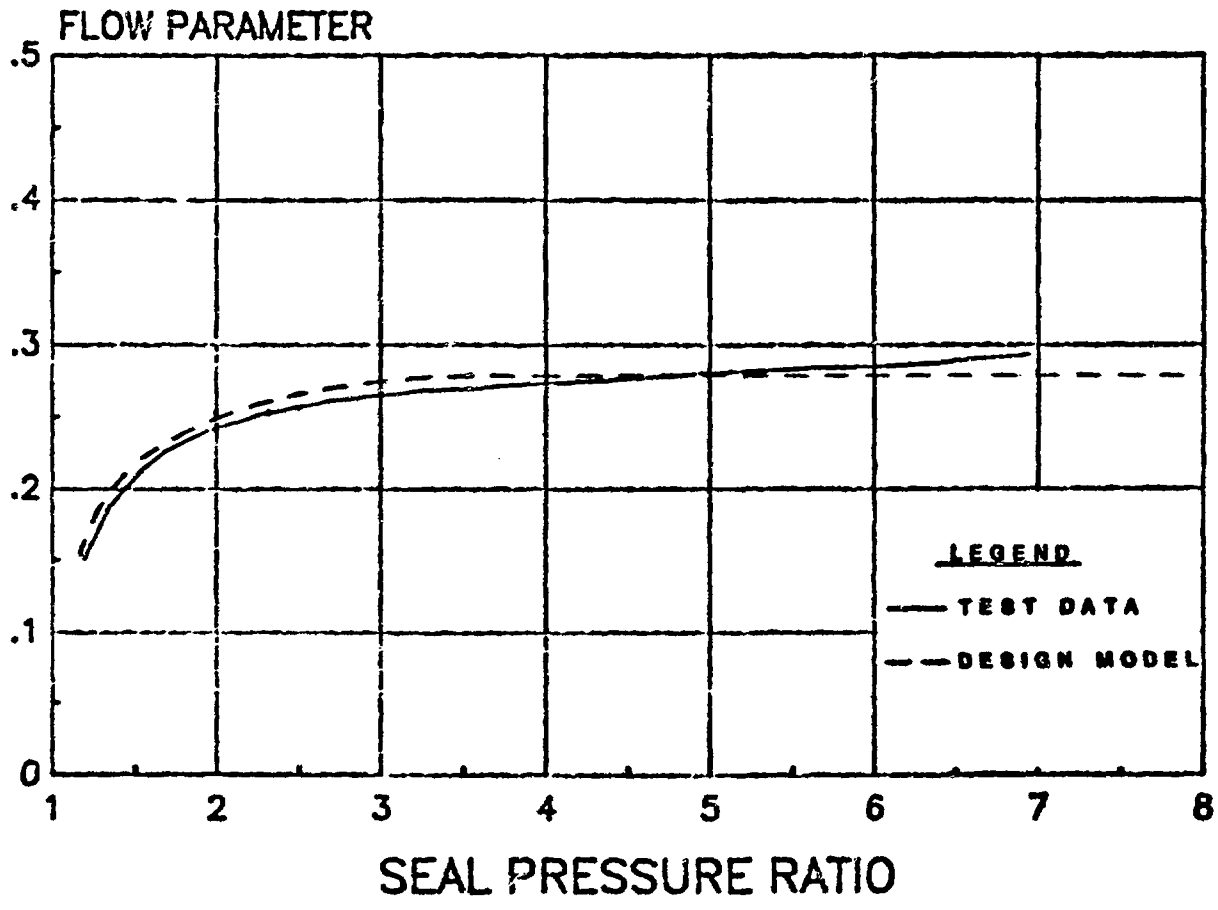
TEST 17 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=4.00, KP/CL=44.0

CL=.010



TEST 18 VERTICAL 4–KNIFE STRAIGHT SEAL KP/KH=4.00, KP/CL=22.0

CL=.020



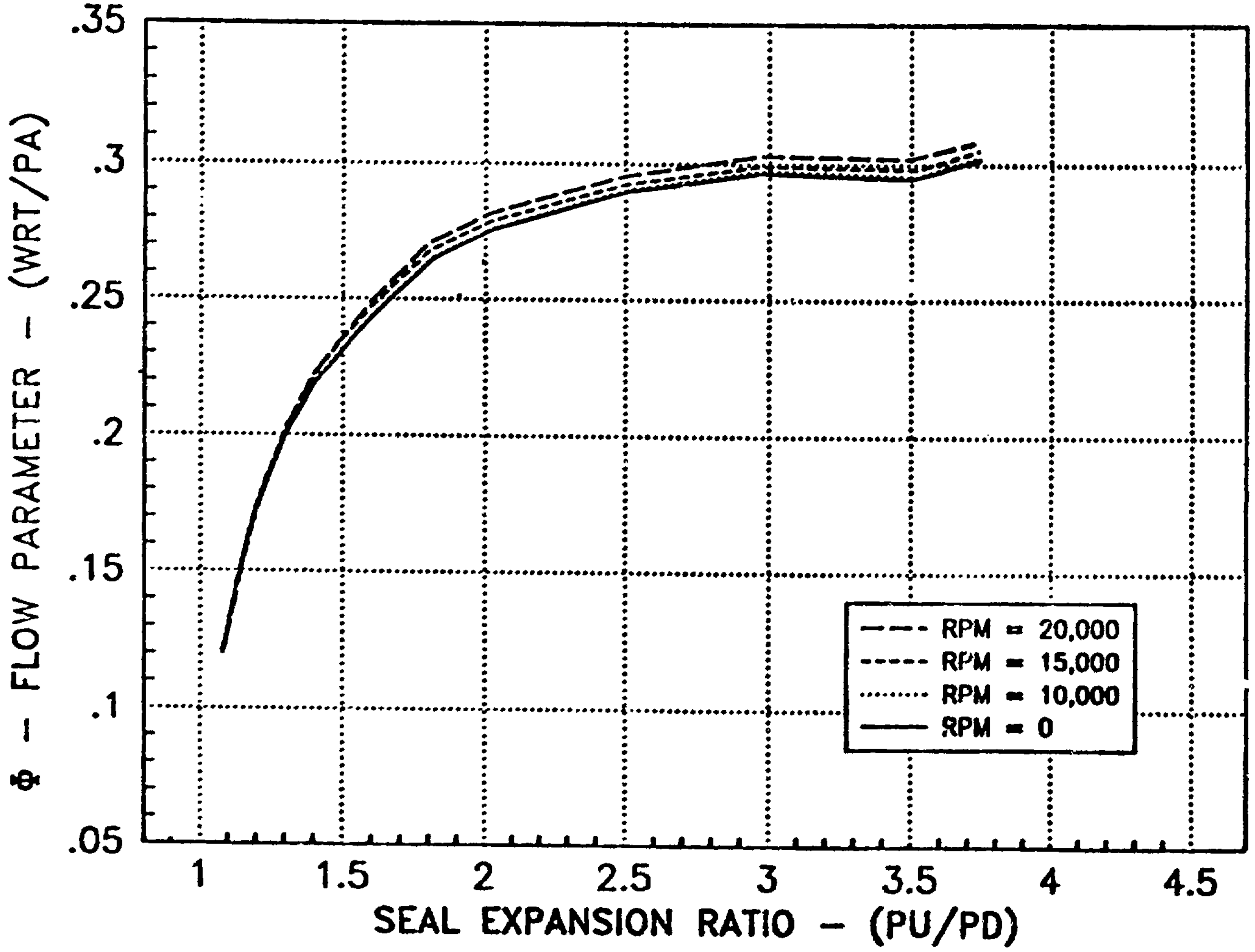
APPENDIX D

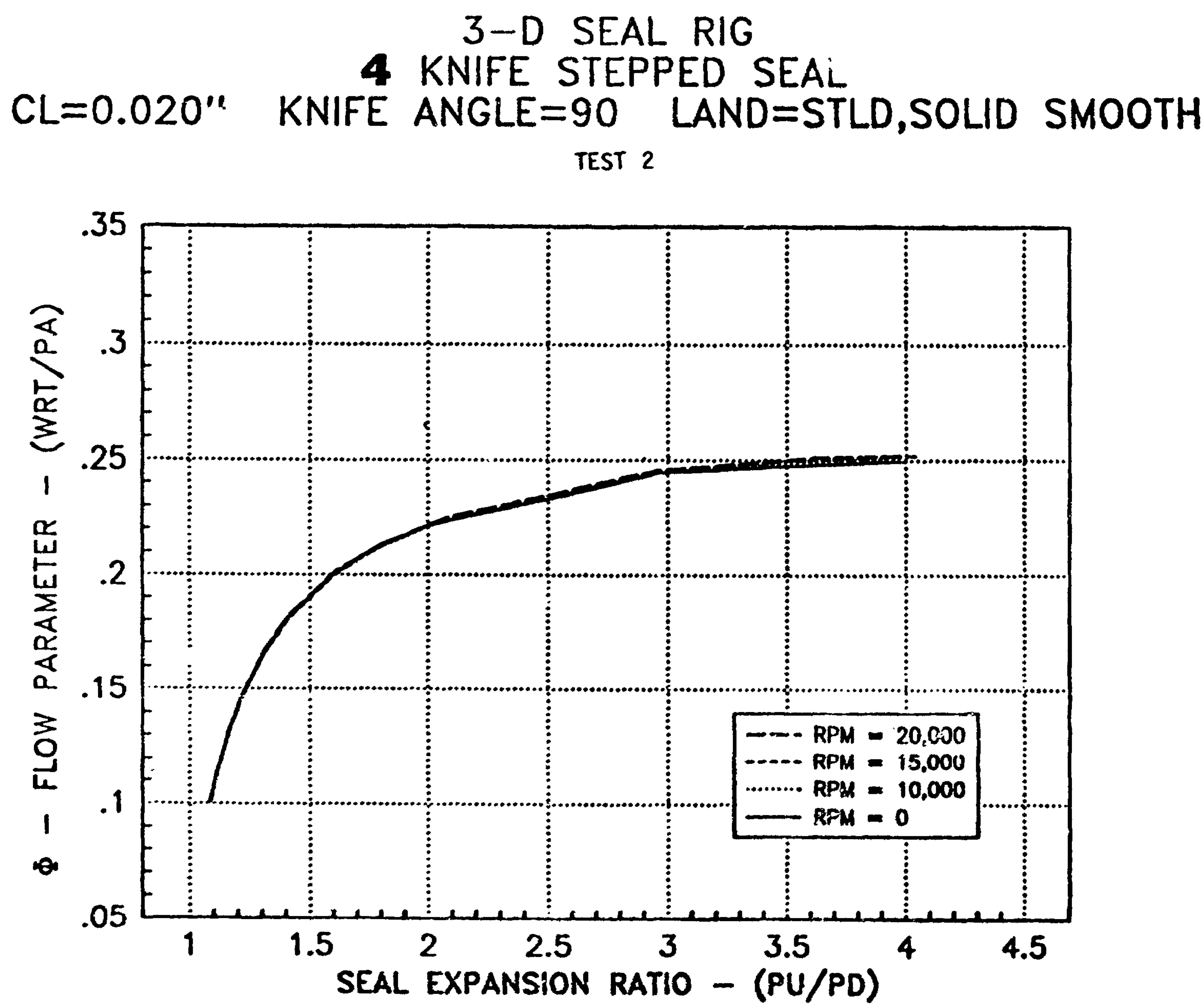
EFFECT OF OPEN-CELL HONEYCOMB LANDS ON THE PERFORMANCE OF STRAIGHT AND STEPPED LABYRINTH SEALS

The following static data were acquired in the 3-D labyrinth seal test rig with a pressurized inlet plenum and an atmospheric exhaust. The inlet air temperatures were the same as the environmental temperature.

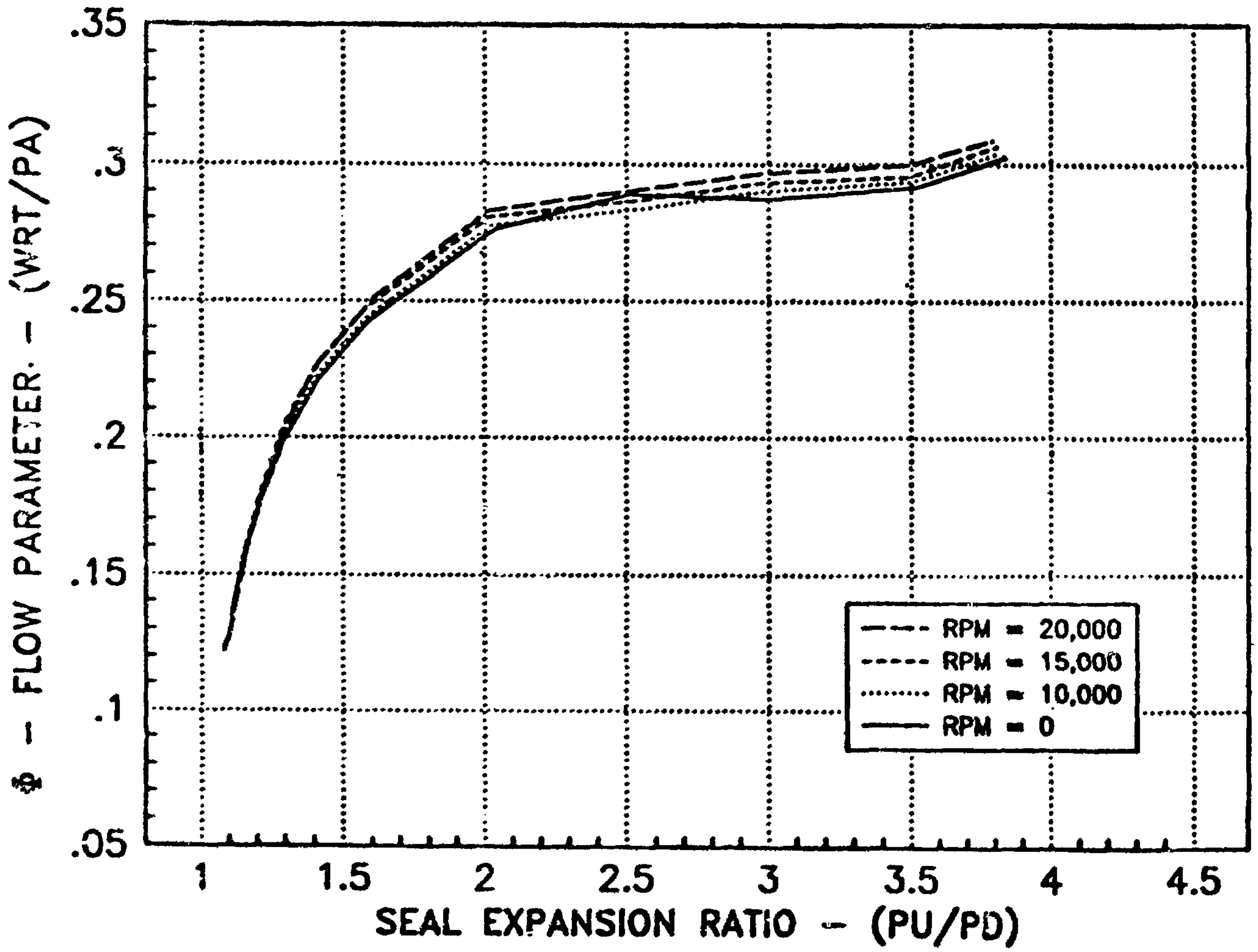
The data reduction and plotting were automated. Irregular plots of the seal performance are the result of the plot algorithm. The test points are connected with straight lines without regard for smoothing data scatter.

3-D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020"   KNIFE ANGLE=90   LAND=STLD,0.062" H/C
TEST 1

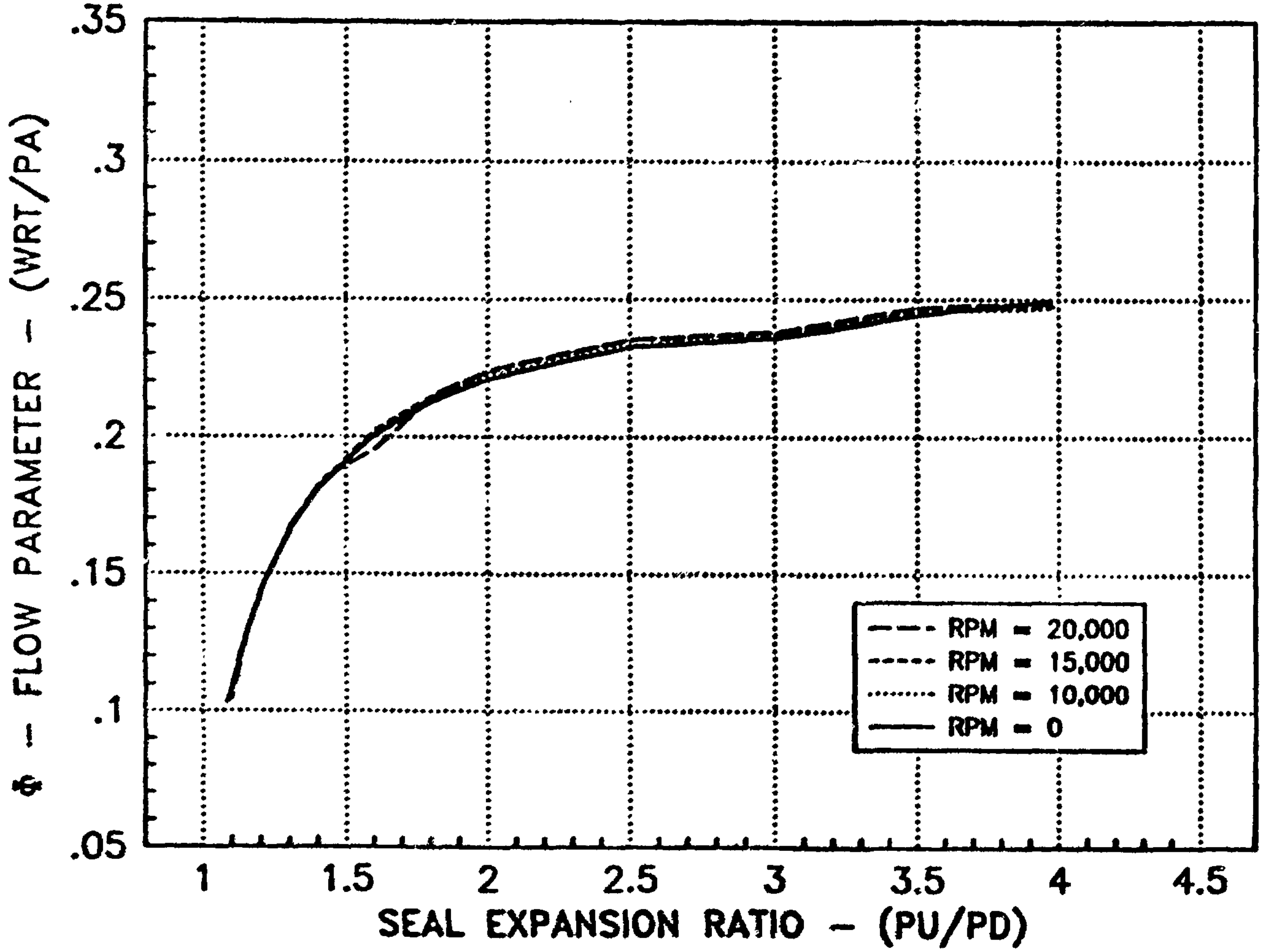



3-D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020" KNIFE ANGLE=90 LAND=STLD,SOLID SMOOTH
TEST 2
Φ - FLOW PARAMETER - (WRT/PA)
.35
.3
.25
.2
.15
.1
.05
1
1.5
2
2.5
3
3.5
4
4.5
SEAL EXPANSION RATIO - (PU/PD)
RPM = 20,000
RPM = 15,000
RPM = 10,000
RPM = 0

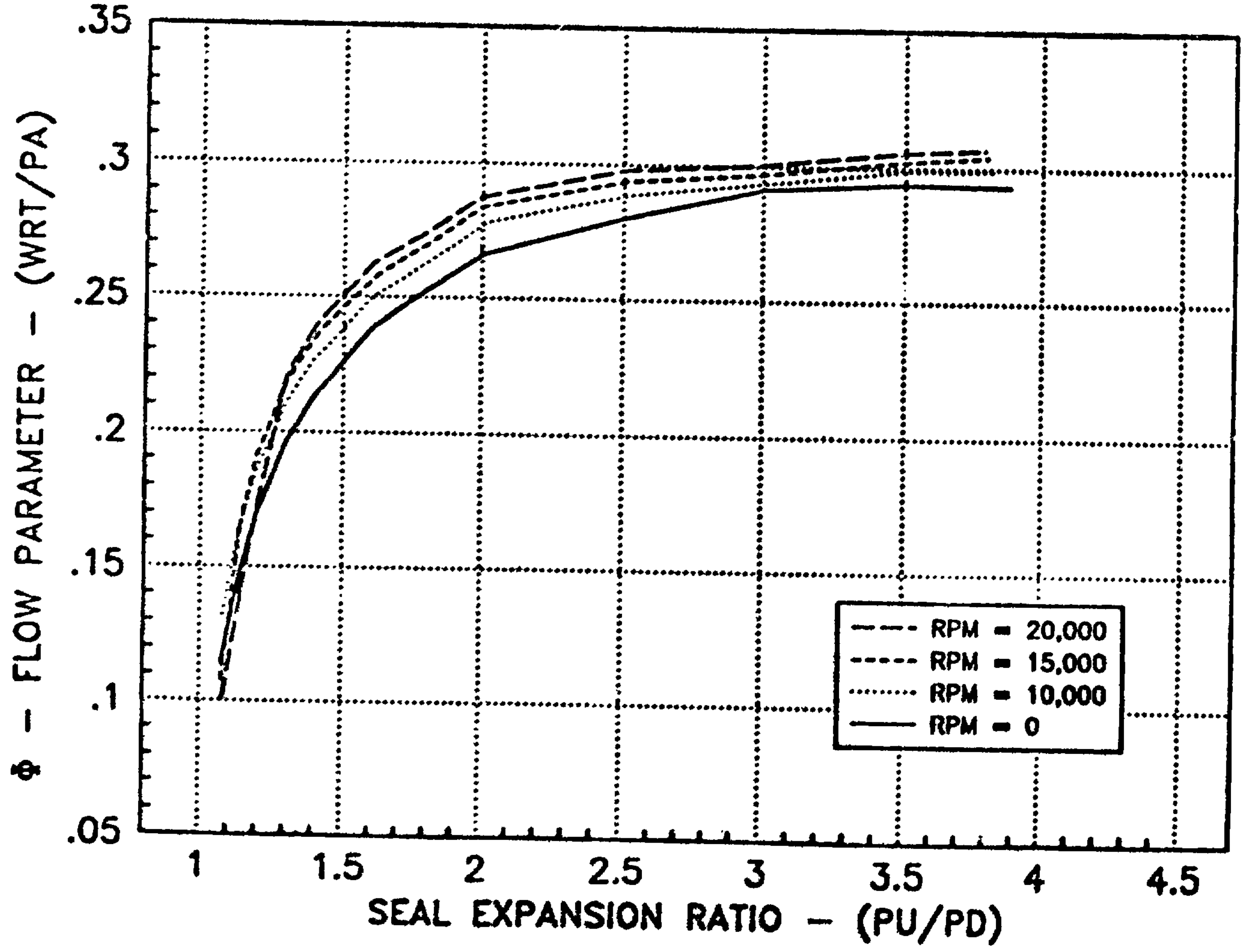
3–D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020"   KNIFE ANGLE=90   LAND=LTSD,0.062" H/C
TEST 3



3-D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020"   KNIFE ANGLE=90   LAND=LTSD,SOLID SMOOTH
TEST 4



3-D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020" KNIFE ANGLE=50 LAND=STLD,0.062" H/C
TEST 5

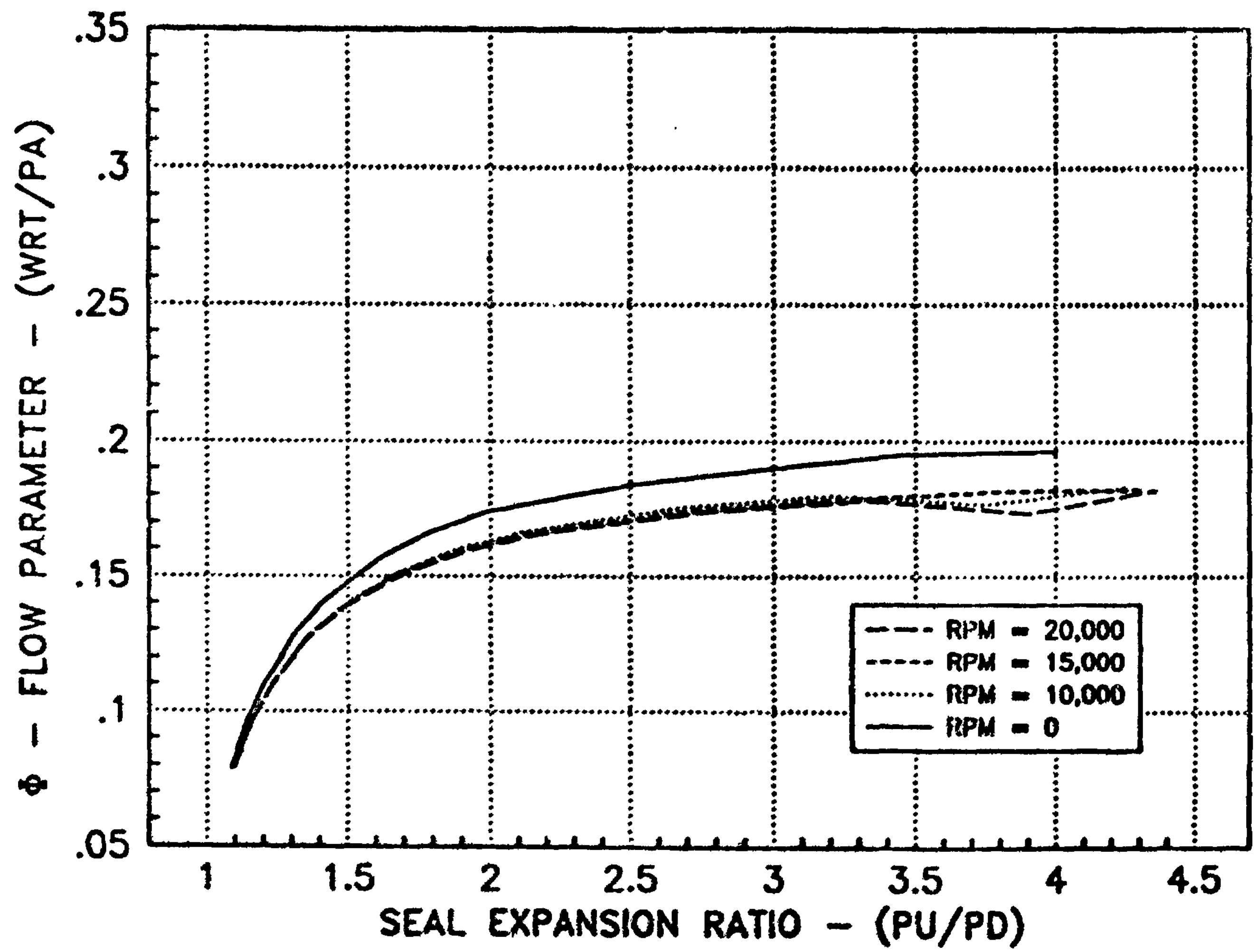


3–D SEAL RIG

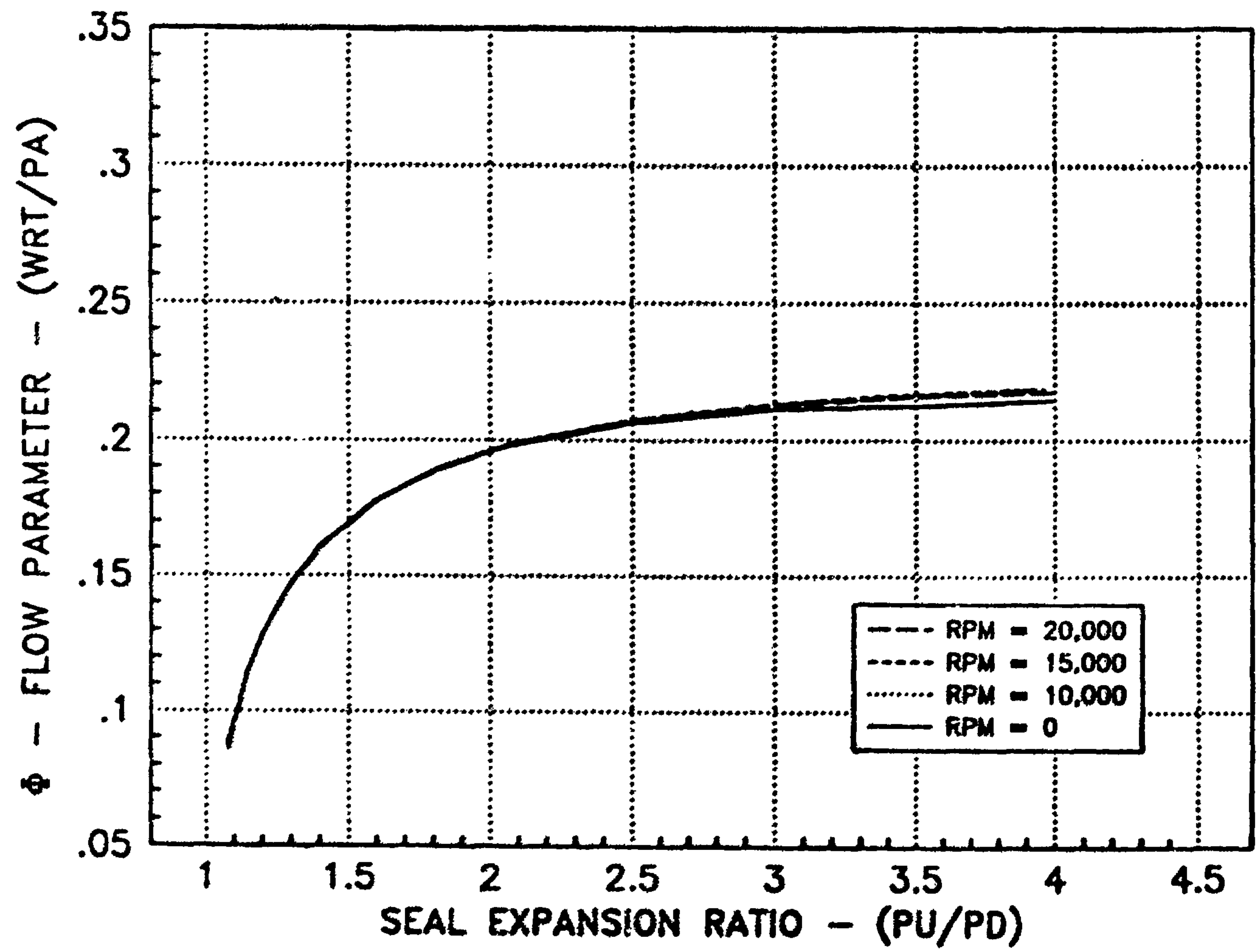
4 KNIFE STEPPED SEAL

CL=0.020"   KNIFE ANGLE=50   LAND=STLD,SOLID SMOOTH

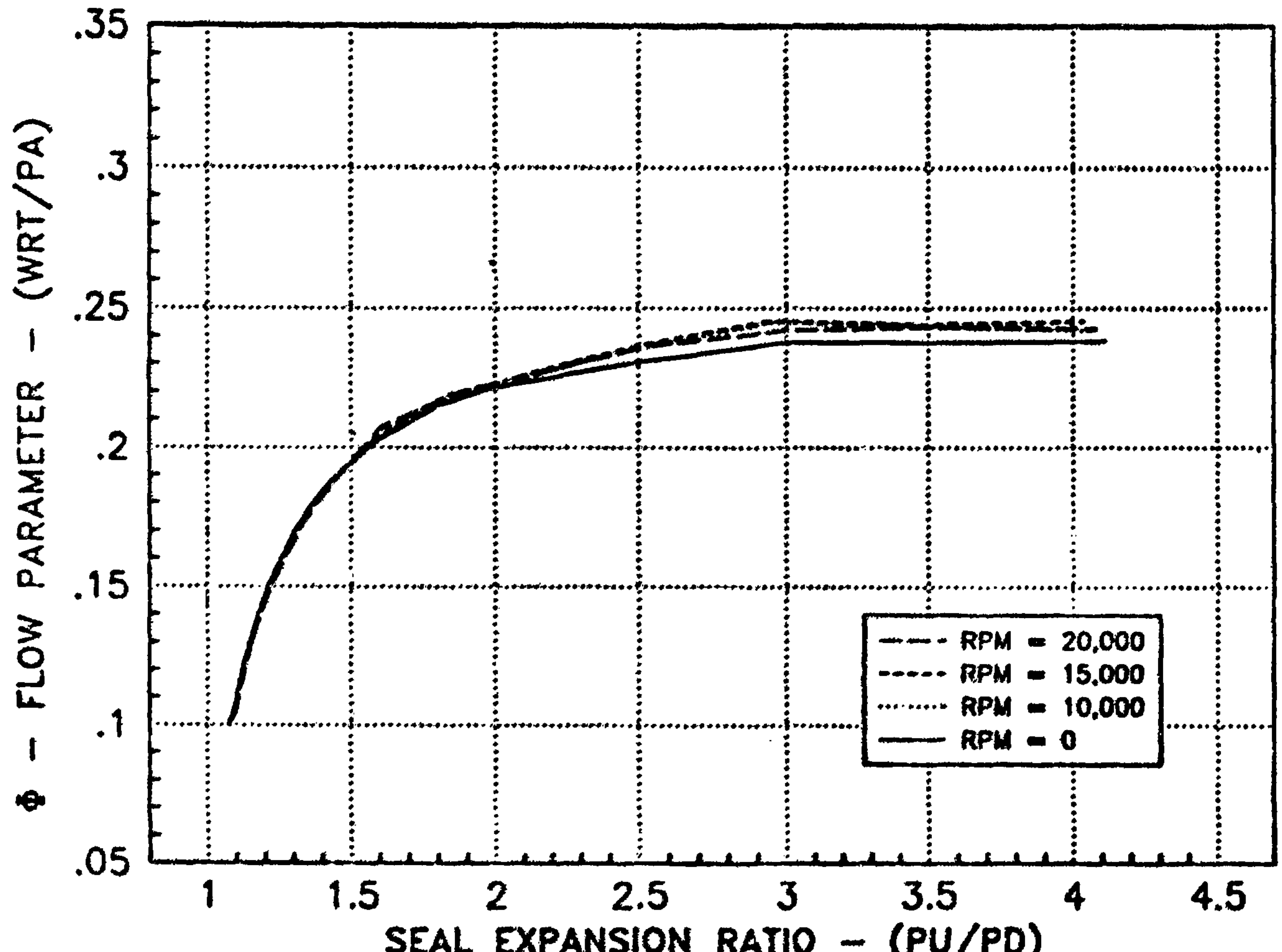
TEST 6



3-D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020" KNIFE ANGLE=50 LAND=LTSD,0.062" H/C
TEST 7

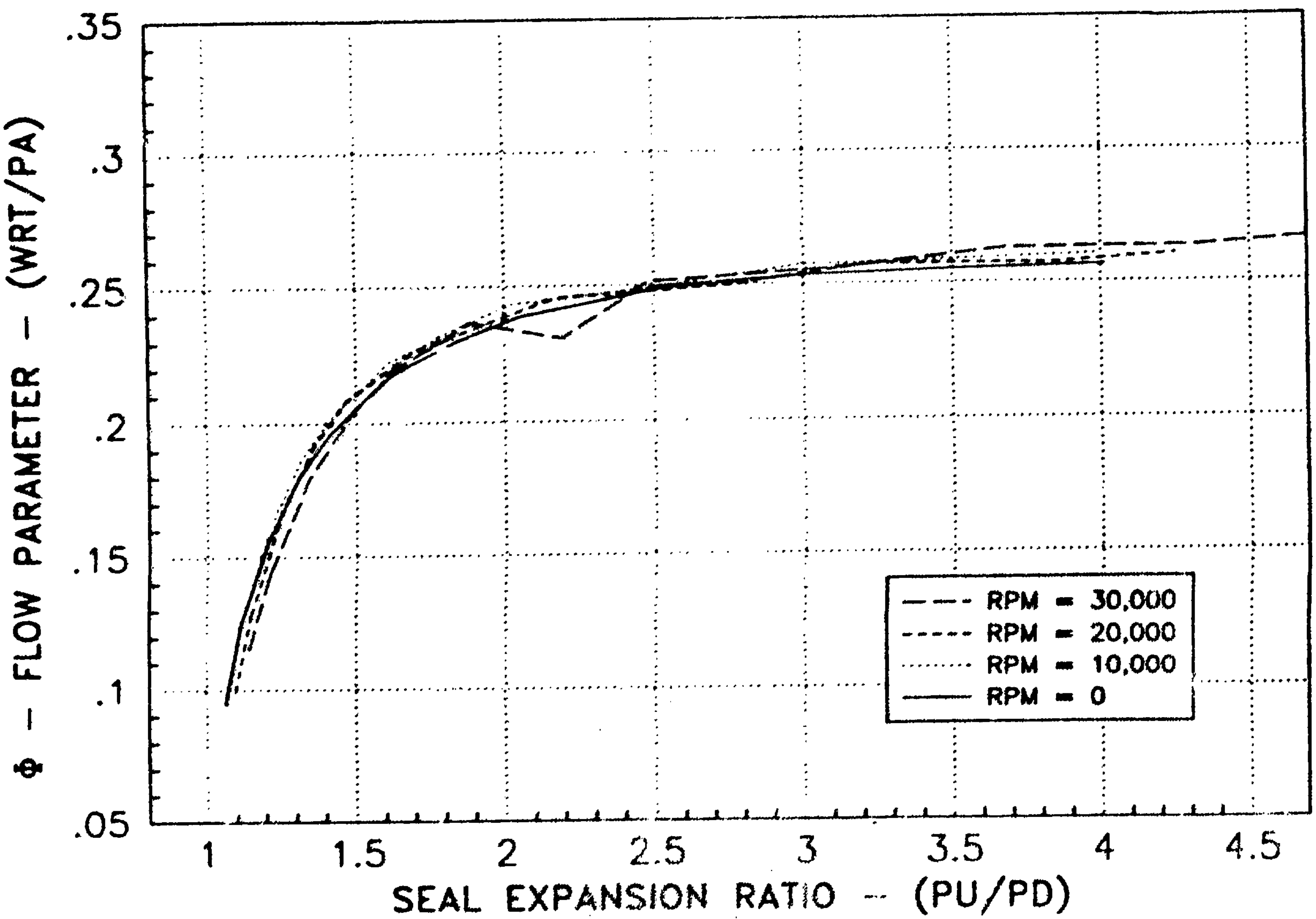


3-D SEAL RIG
4 KNIFE STEPPED SEAL
CL=0.020"   KNIFE ANGLE=50   LAND=LTSD,SOLID SMOOTH
TEST 8



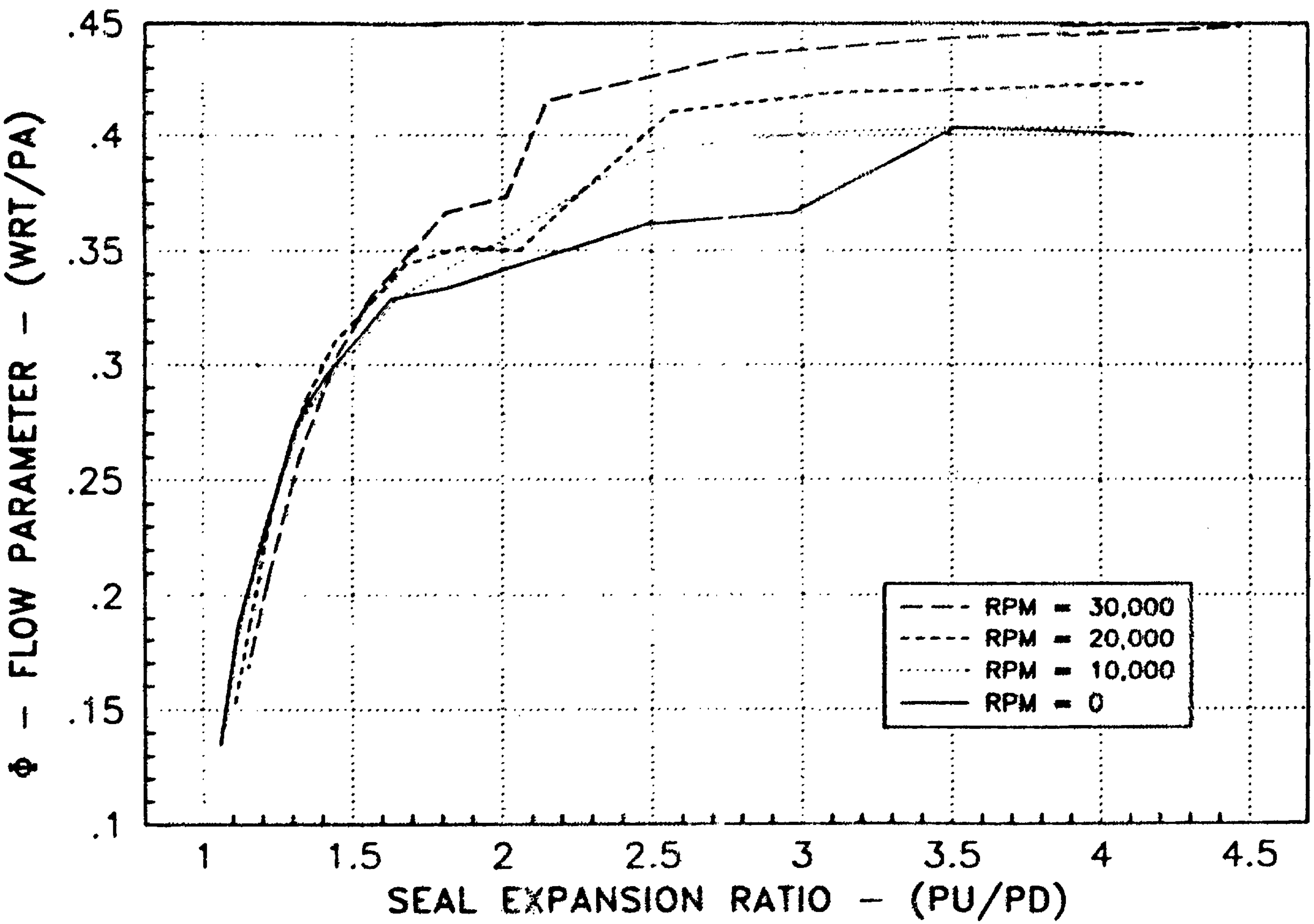
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005" KNIFE ANGLE=90 LAND=0.031" H/C

TEST 1



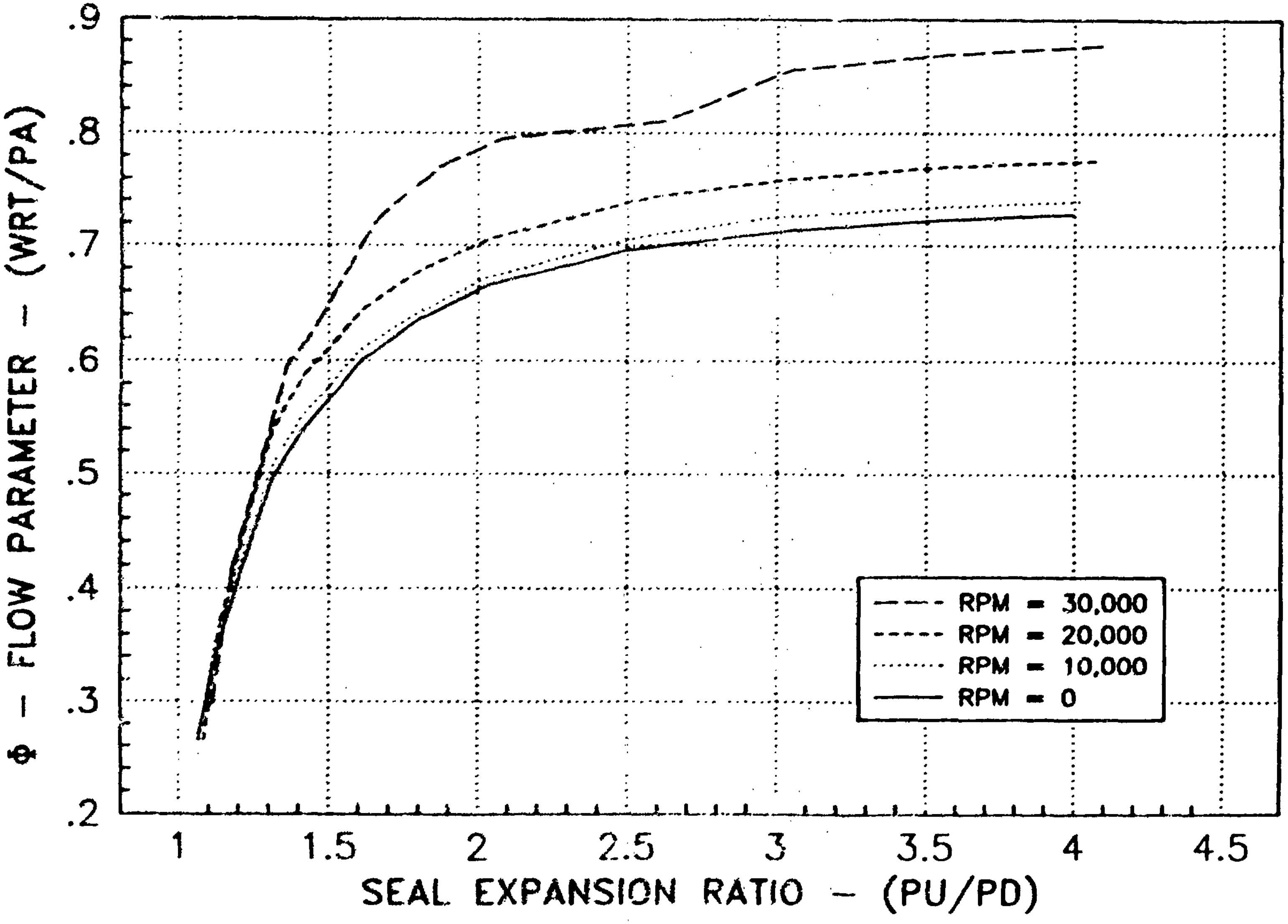
3—D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=90   LAND=0.062" H/C

TEST 2



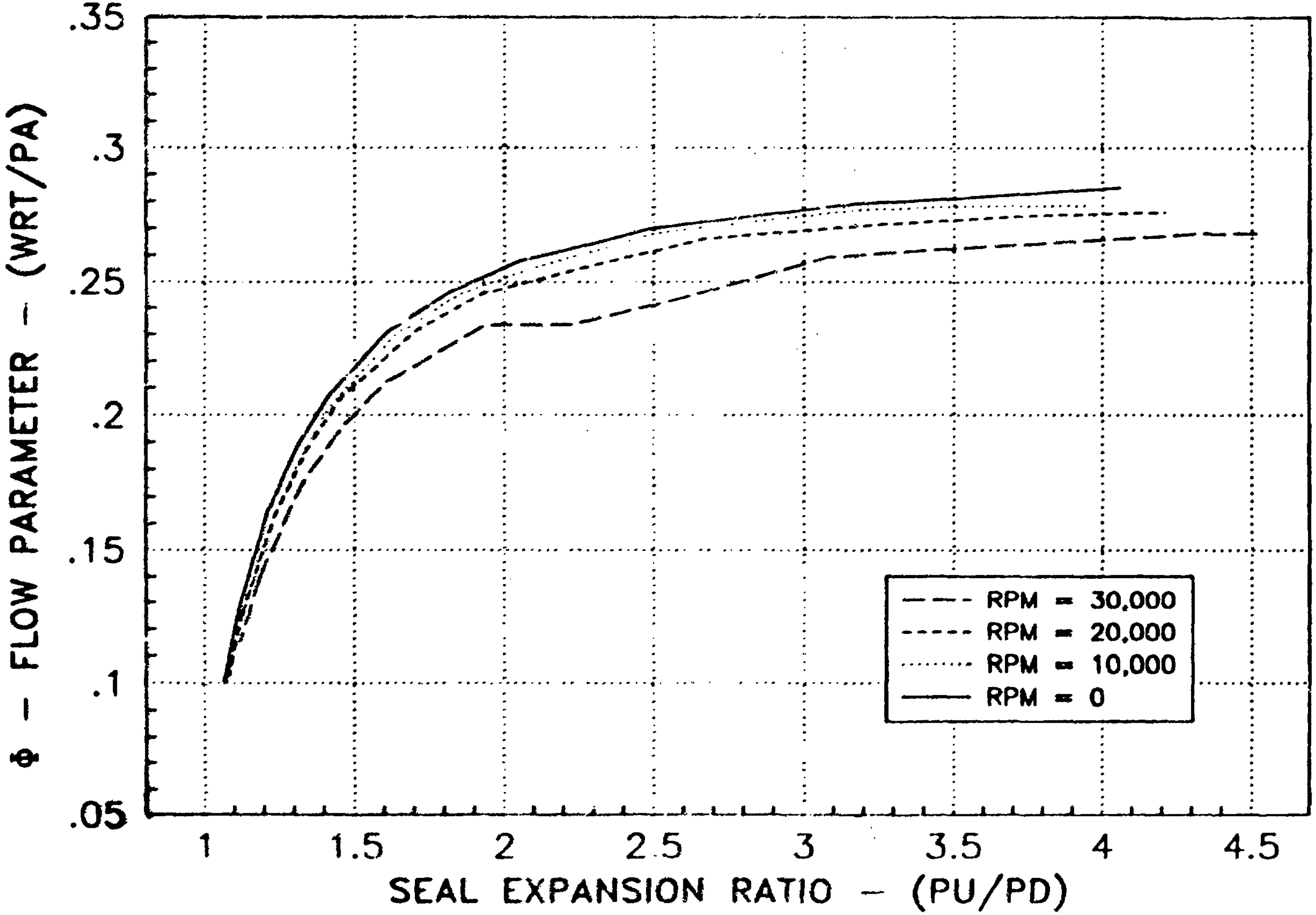
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005" KNIFE ANGLE=90 LAND=0.125" H/C

TEST 3



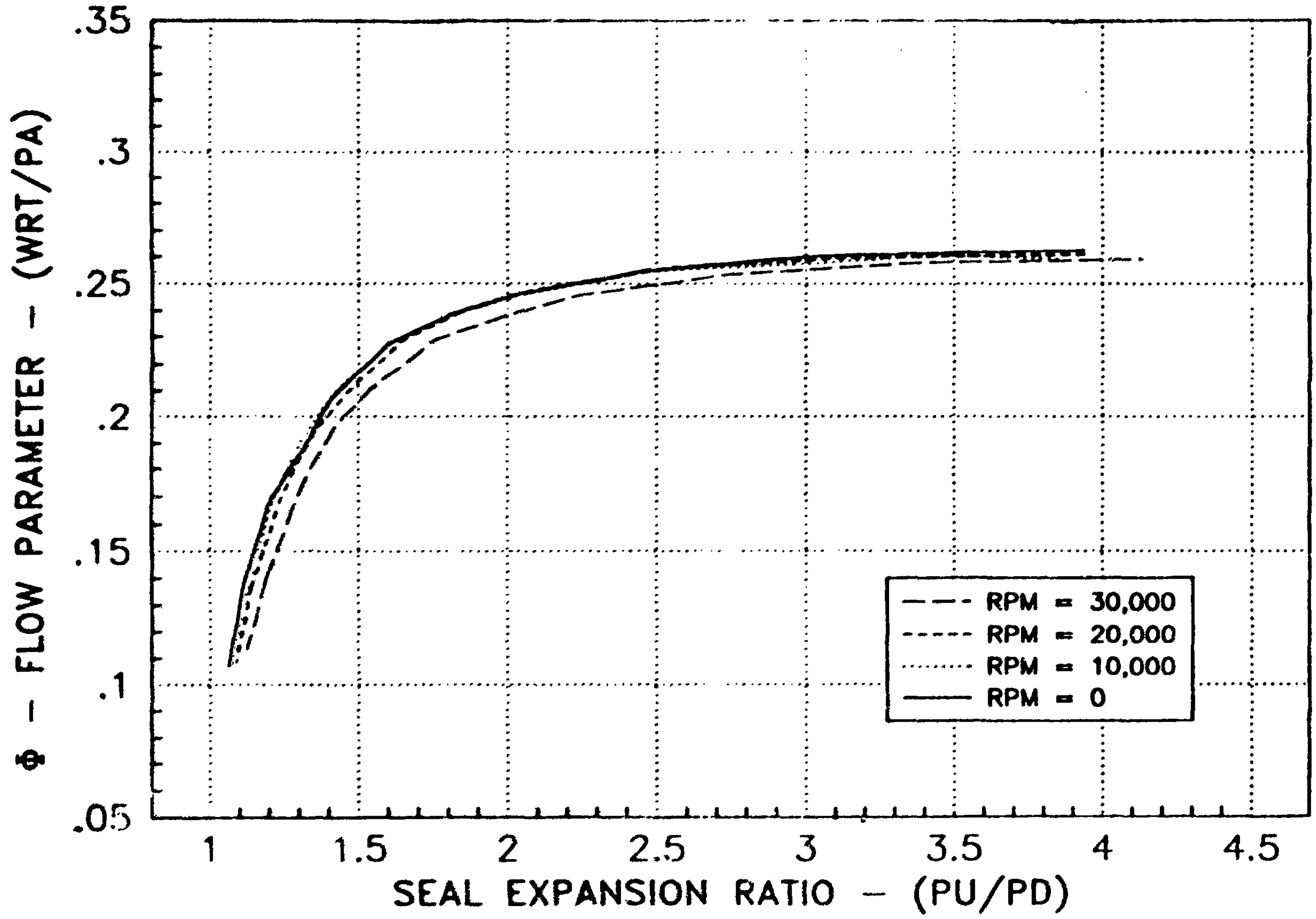
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=90   LAND=SOLID SMOOTH

TEST 4



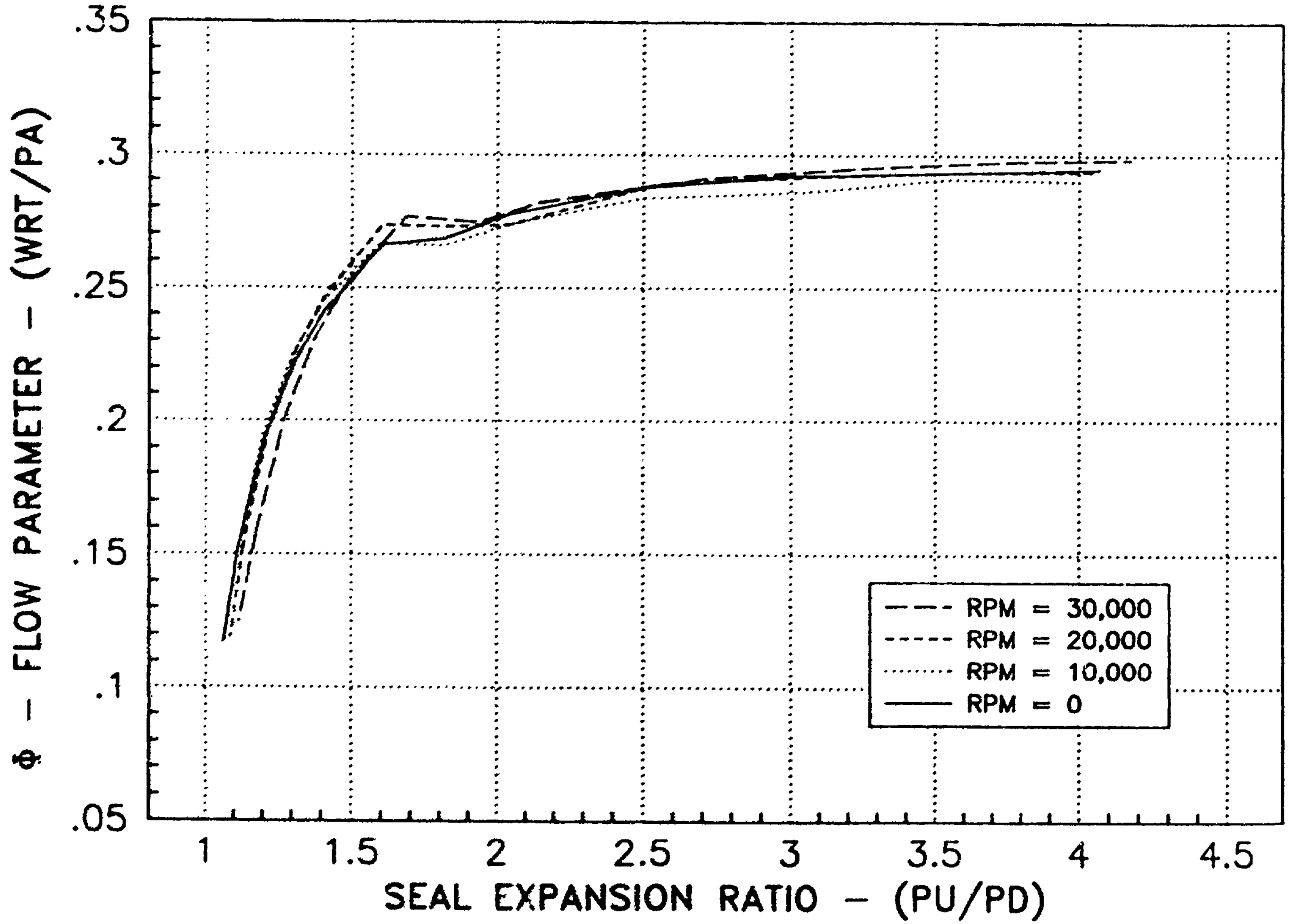
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=90 LAND=0.031" H/C

TEST 5



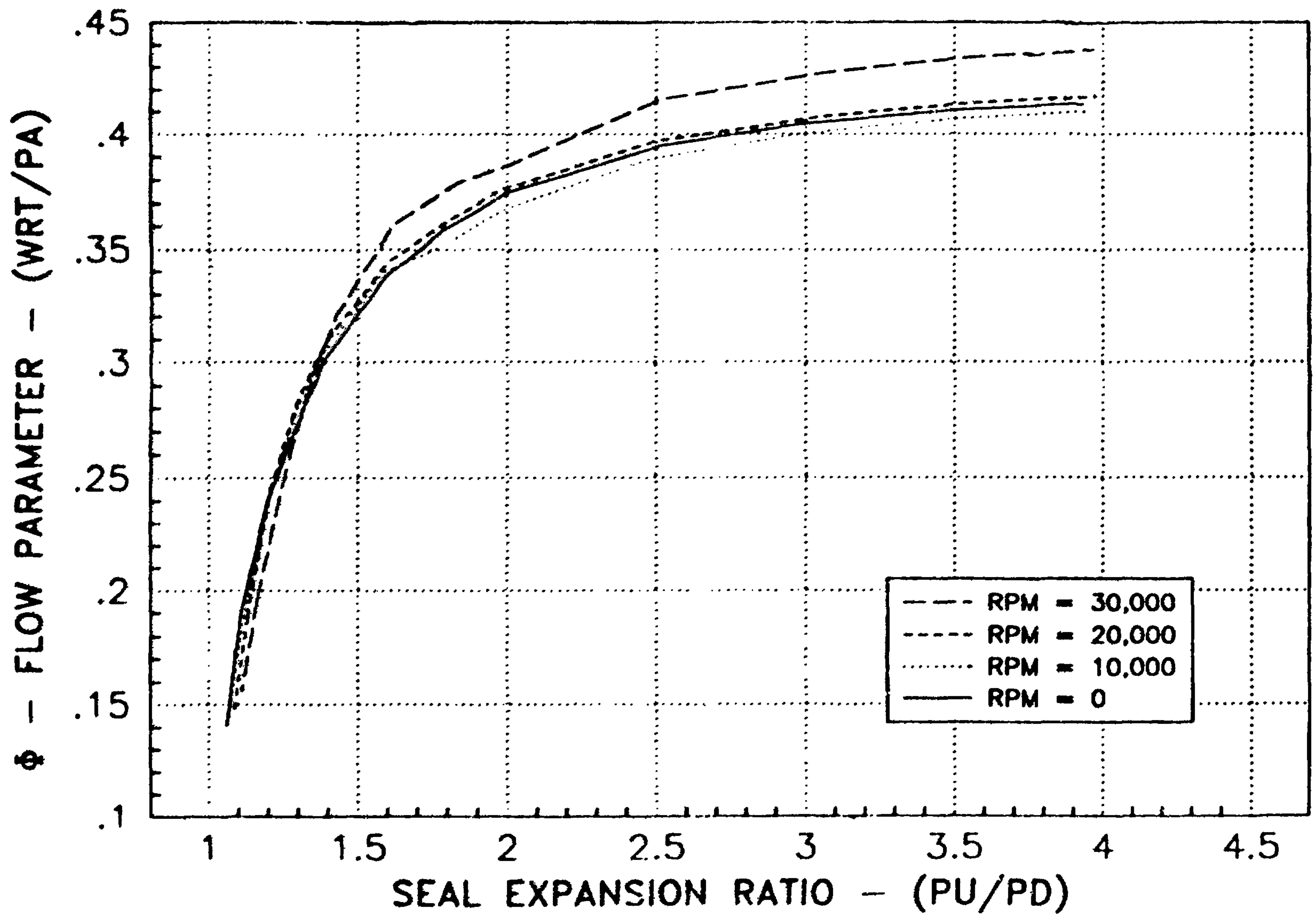
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010"   KNIFE ANGLE=90   LAND=0.062" H/C

TEST 6



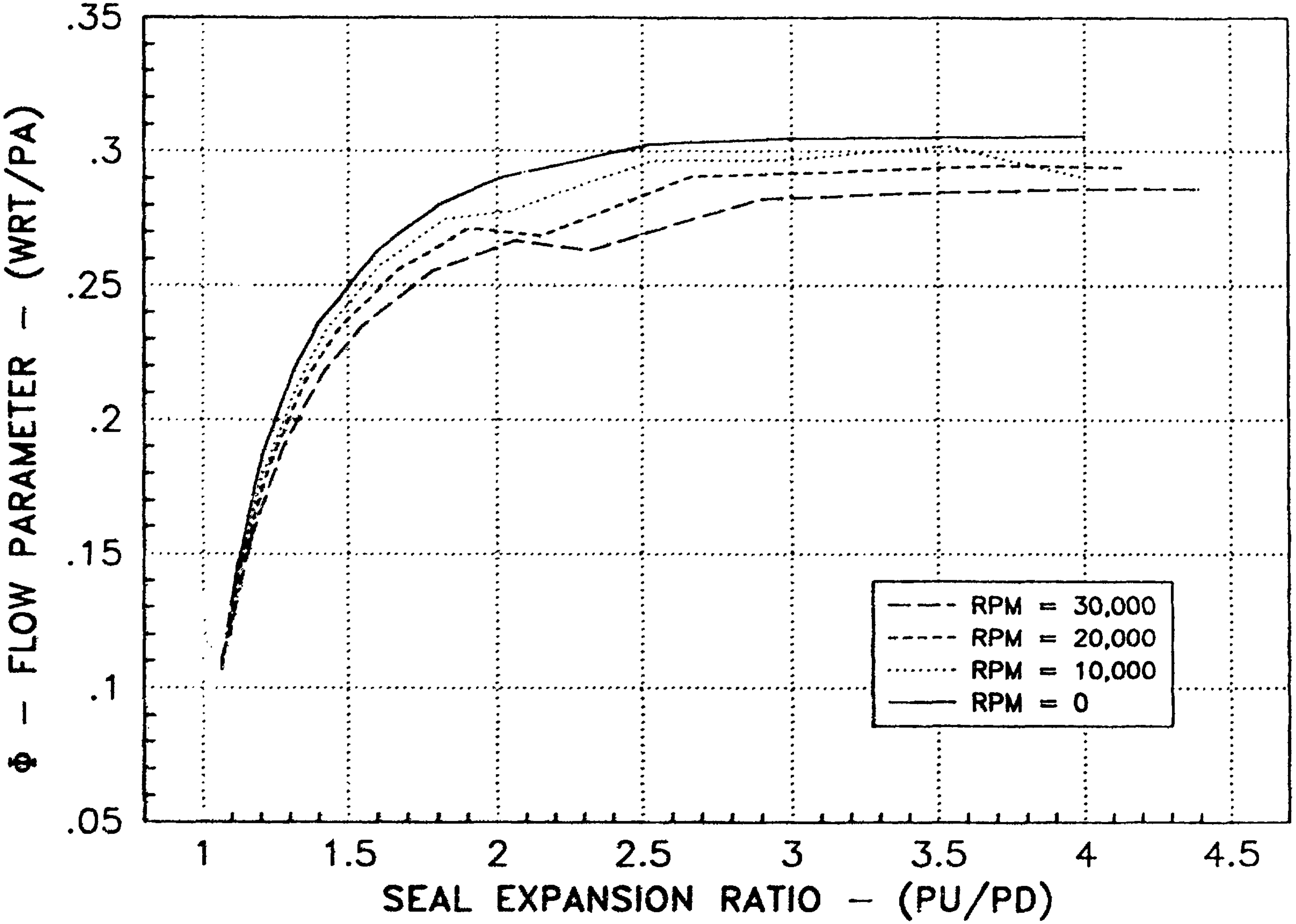
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=90 LAND=0.125" H/C

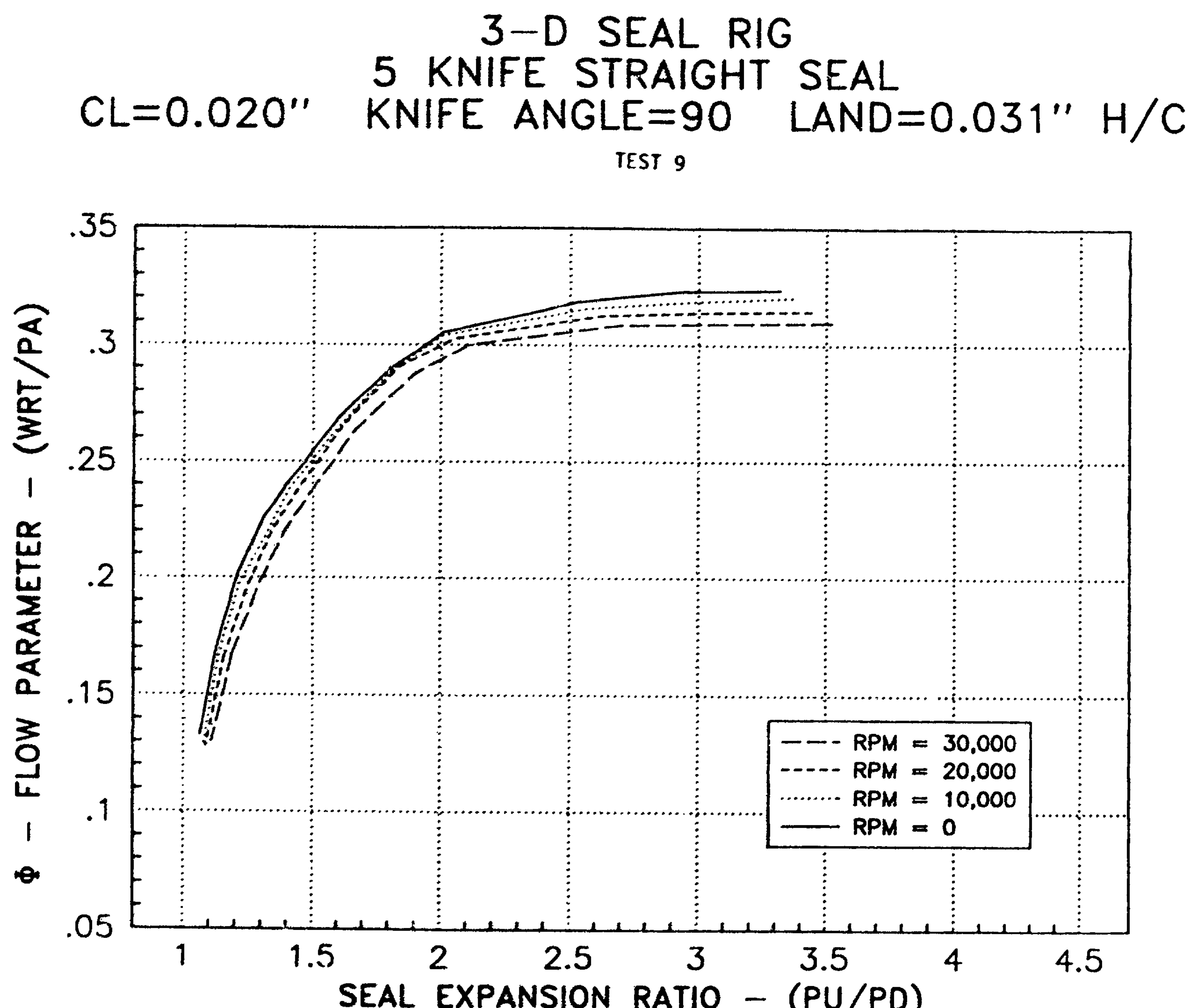
TEST 7

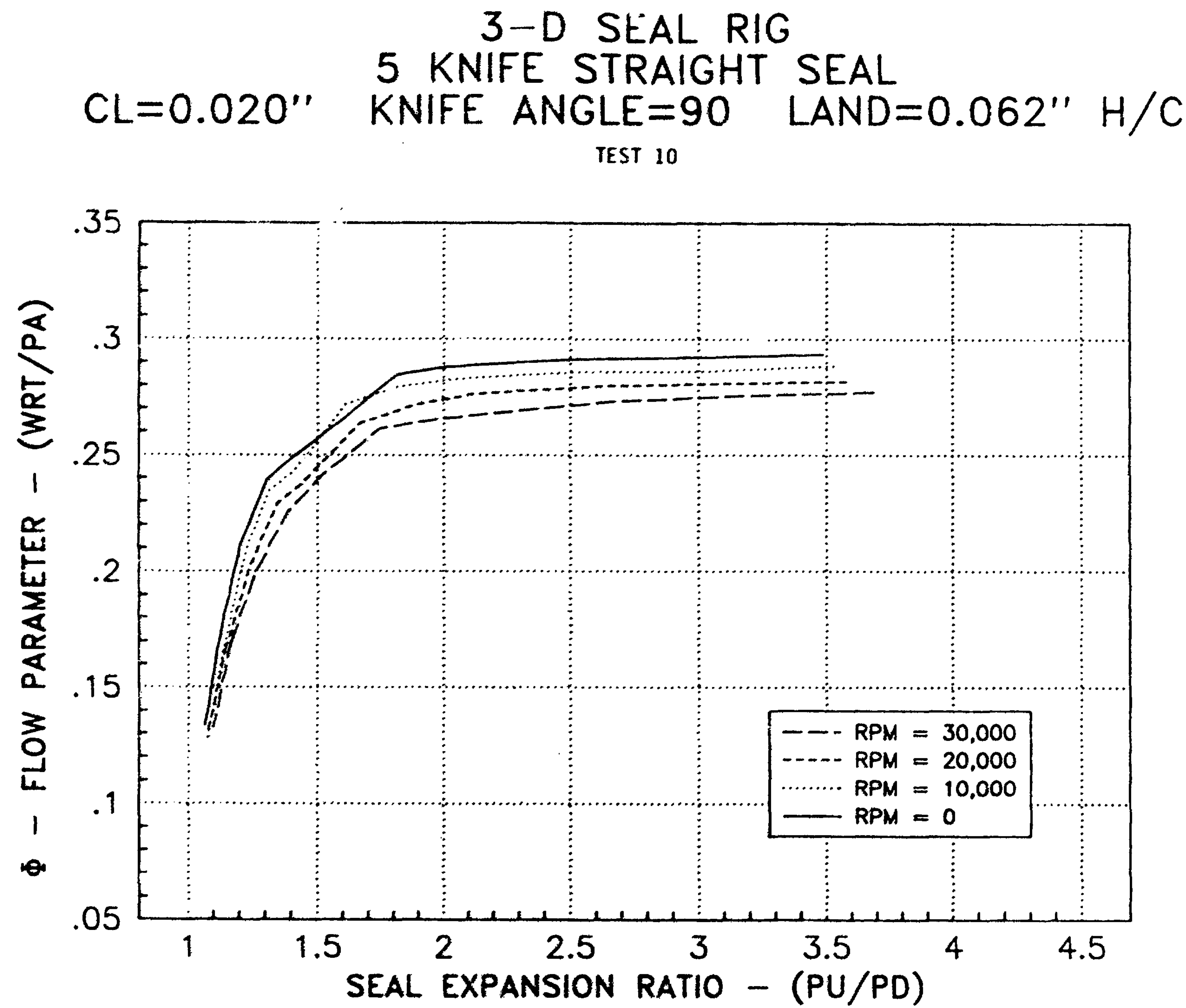


3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=90 LAND=SOLID SMOOTH

TEST 8

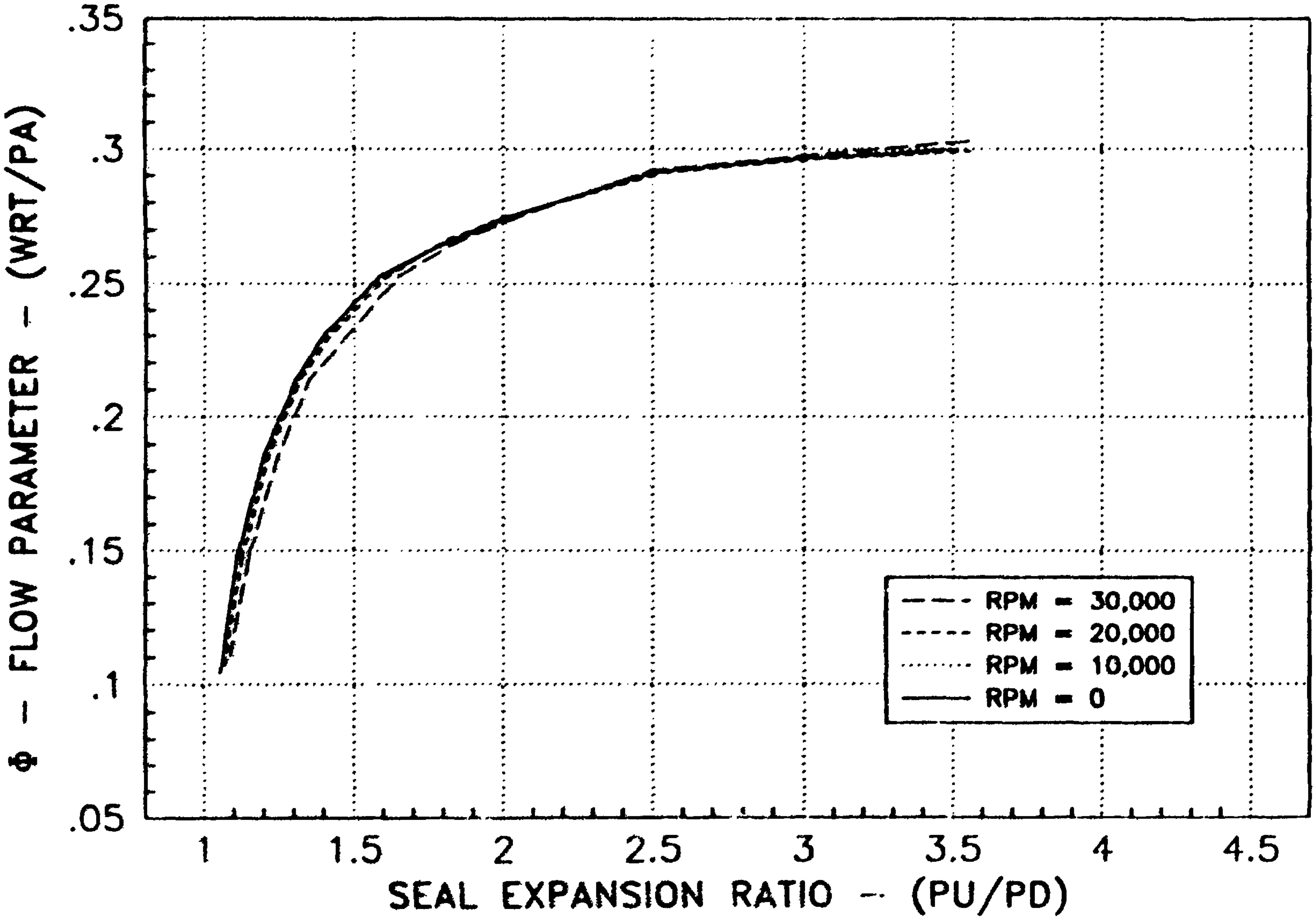



3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020" KNIFE ANGLE=90 LAND=0.031" H/C
TEST 9
Φ - FLOW PARAMETER - (WRT/PA)
.35
.3
.25
.2
.15
.1
.05
1
1.5
2
2.5
3
3.5
4
4.5
SEAL EXPANSION RATIO - (PU/PD)
RPM = 30,000
RPM = 20,000
RPM = 10,000
RPM = 0

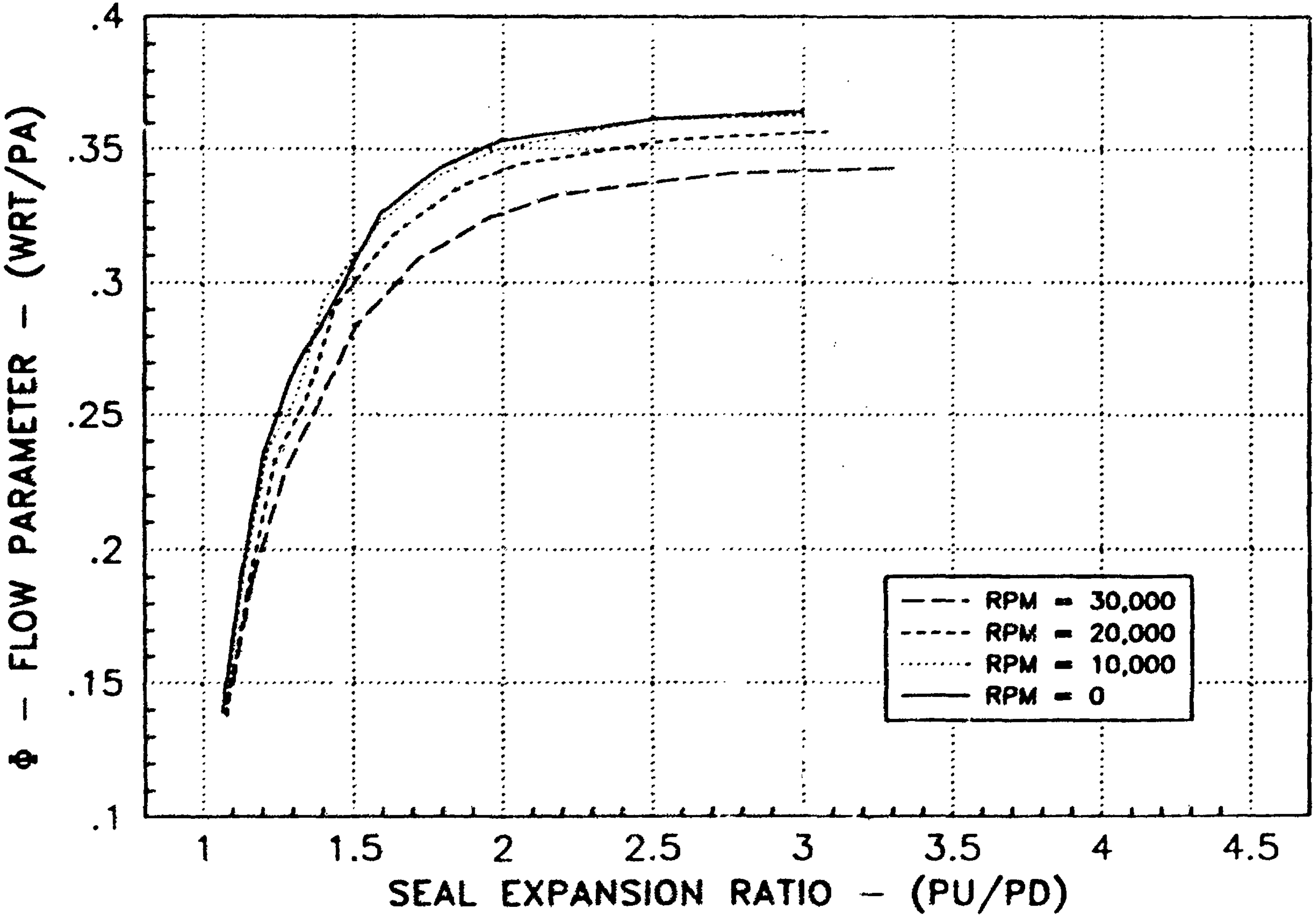


3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020" KNIFE ANGLE=90 LAND=0.062" H/C
TEST 10
Φ - FLOW PARAMETER - (WRT/PA)
.35
.3
.25
.2
.15
.1
.05
1
1.5
2
2.5
3
3.5
4
4.5
SEAL EXPANSION RATIO - (PU/PD)
RPM = 30,000
RPM = 20,000
RPM = 10,000
RPM = 0

3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020" KNIFE ANGLE=90 LAND=0.125" H/C
TEST 11

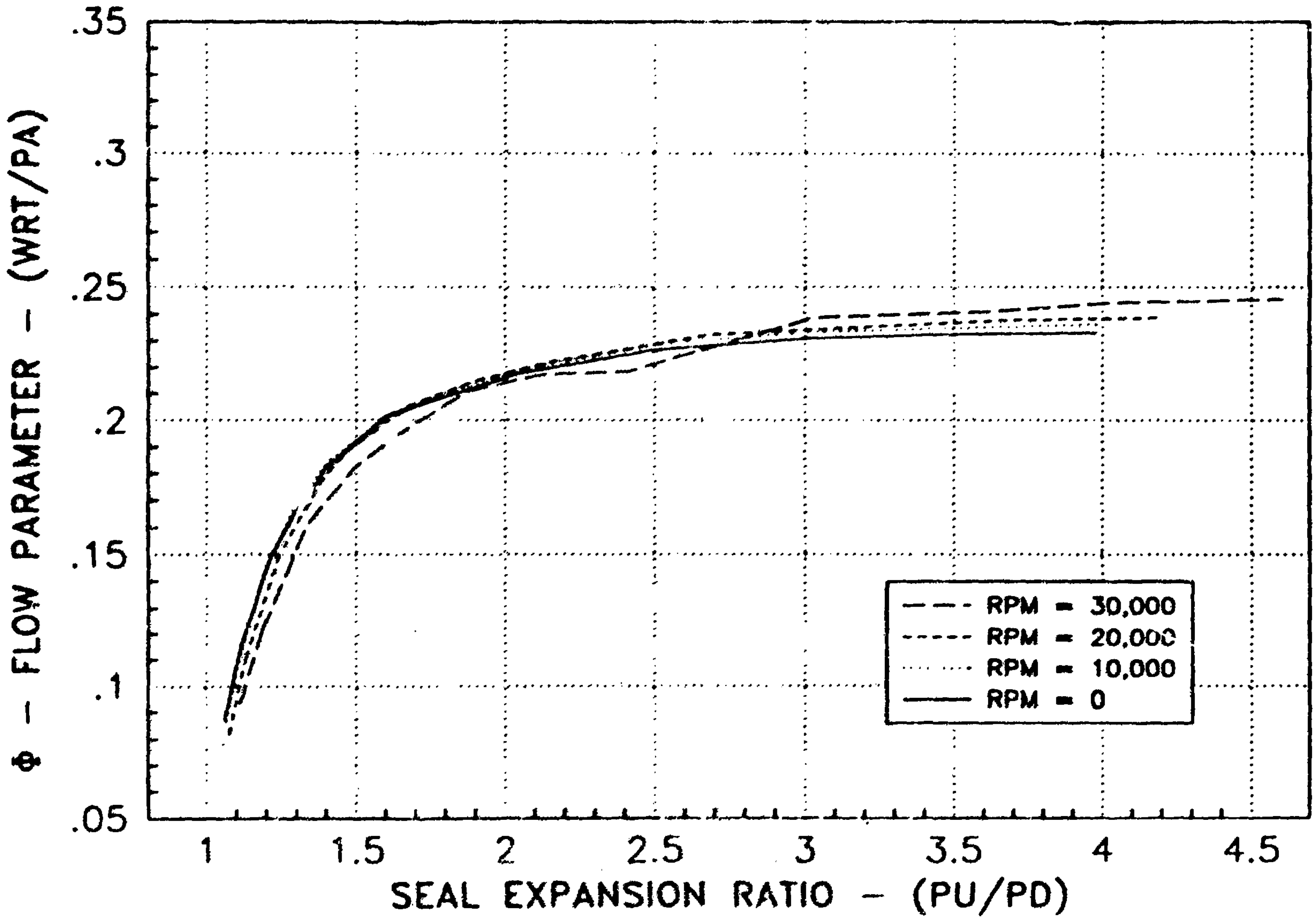


3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020"   KNIFE ANGLE=90   LAND=SOLID SMOOTH
TEST 12



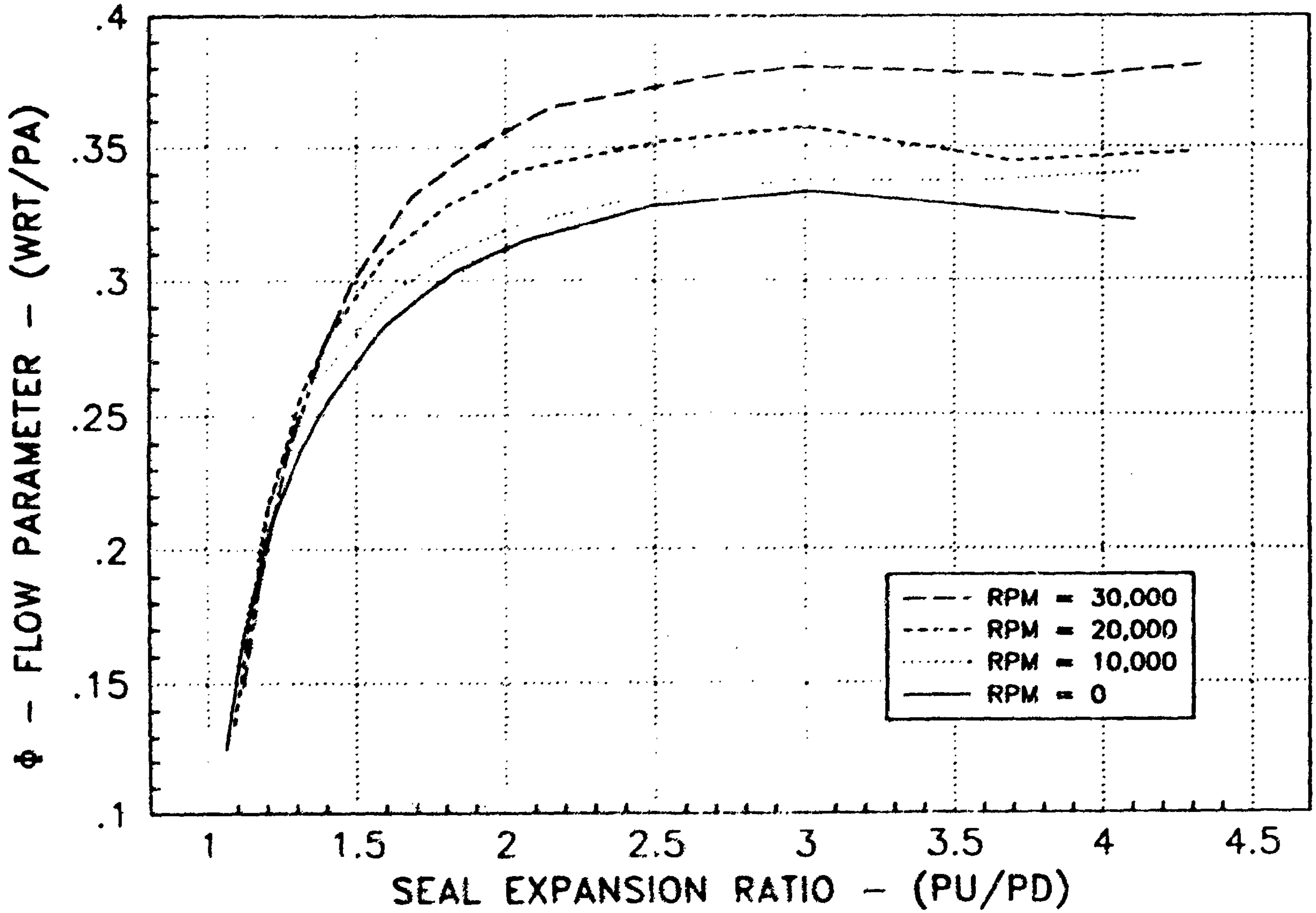
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=70   LAND=0.031" H/C

TEST 13



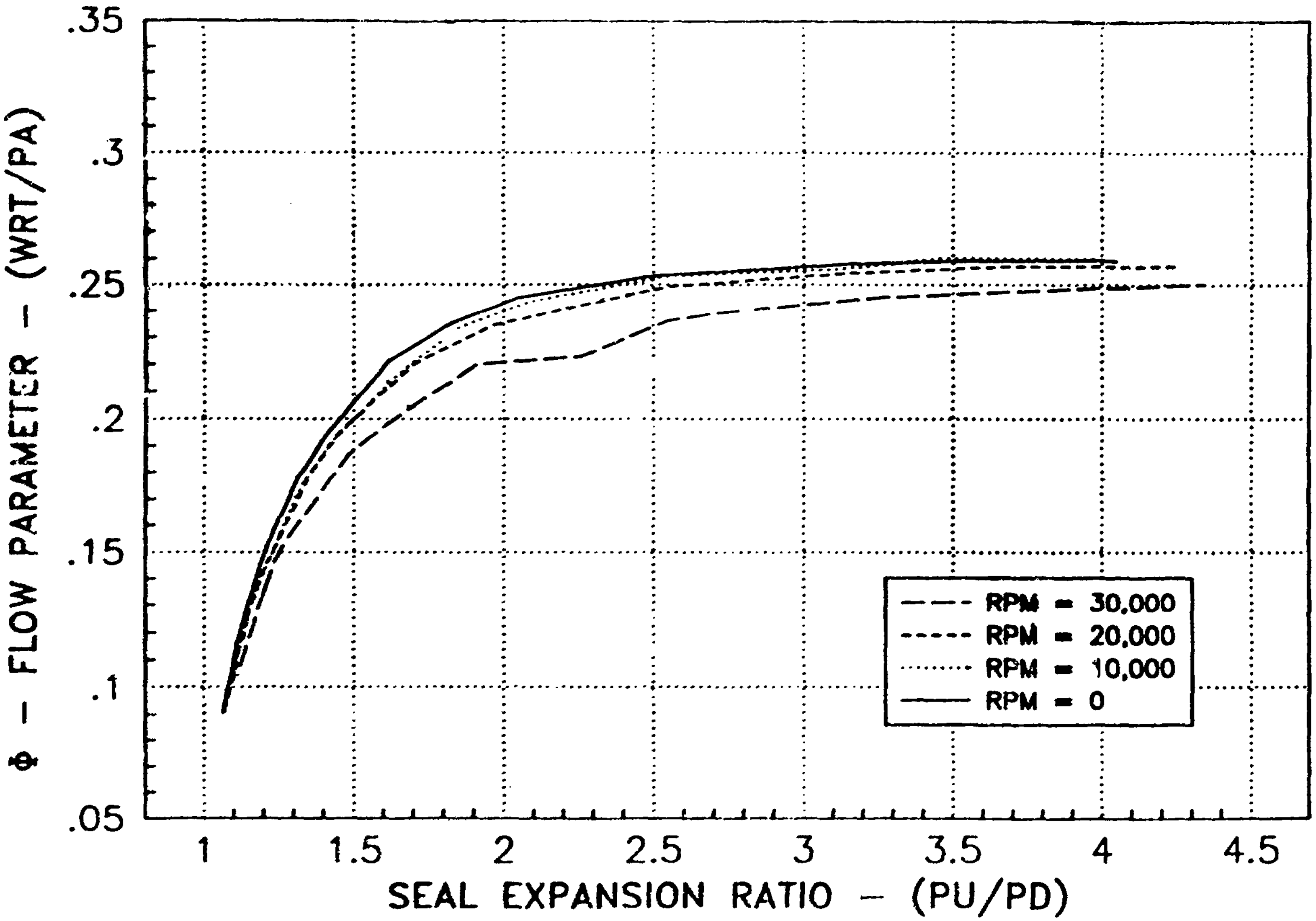
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=70   LAND=0.062" H/C

TEST 14



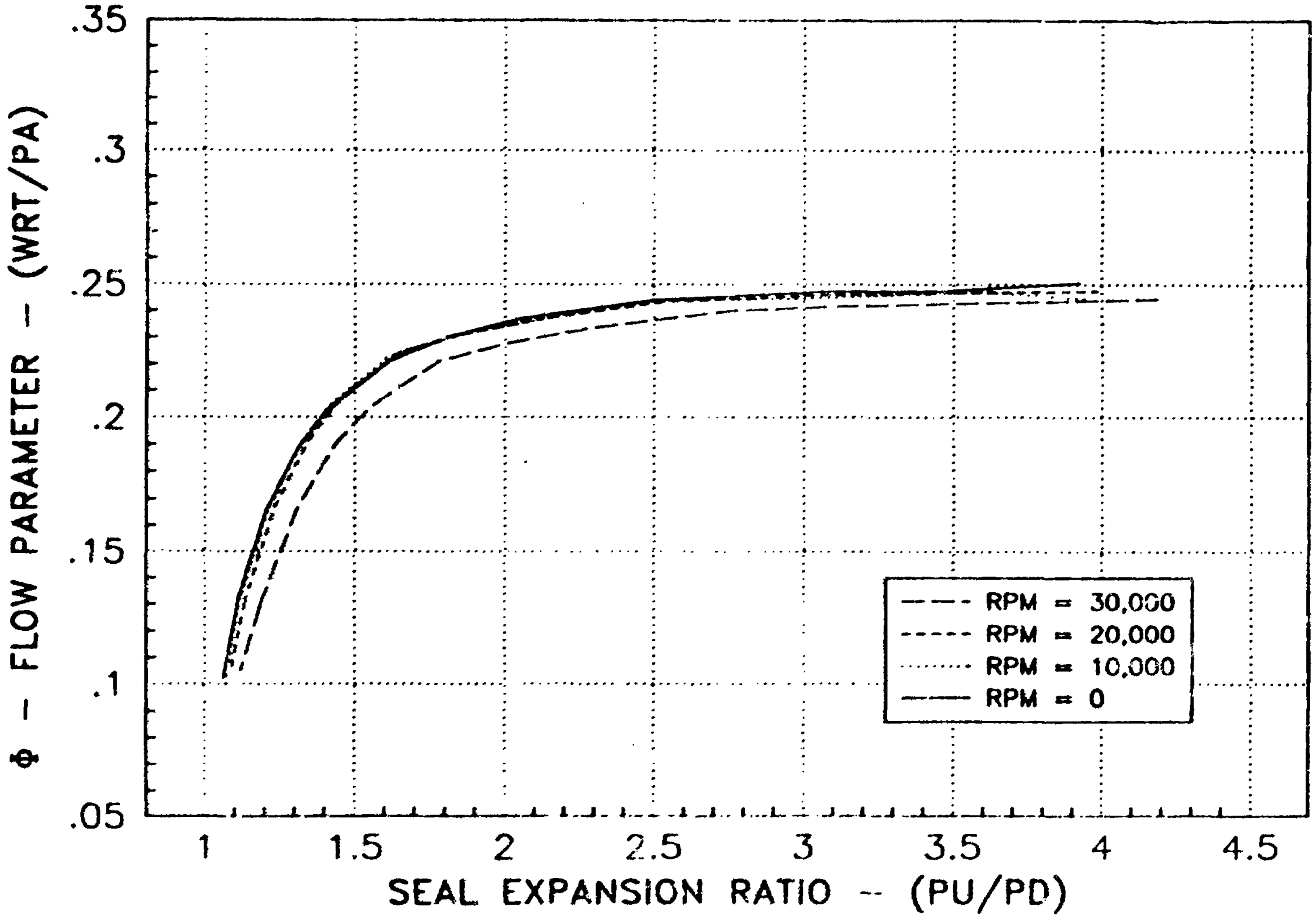
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=70   LAND=SOLID SMOOTH

TEST 15



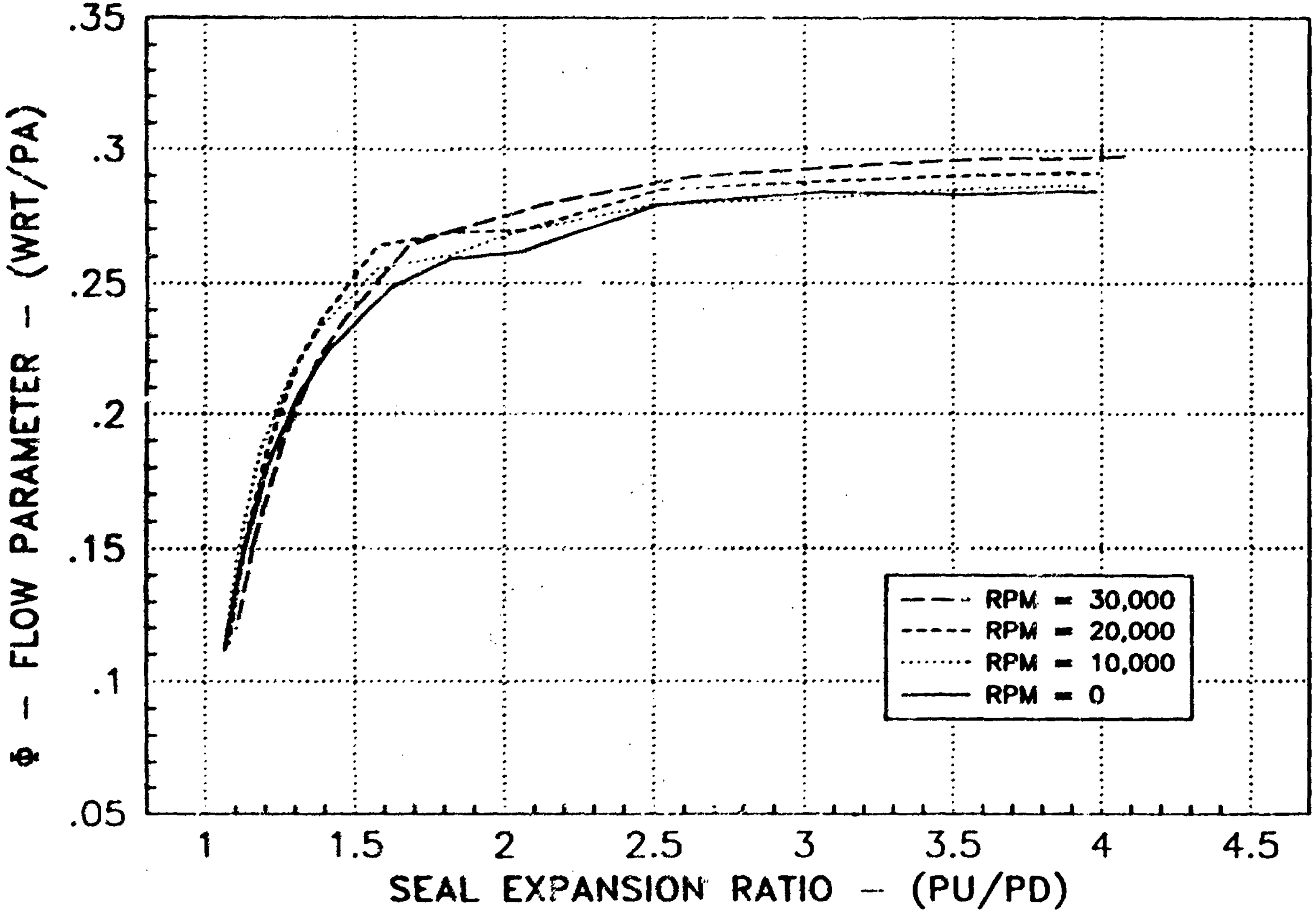
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=70 LAND=0.031" H/C

TEST 16

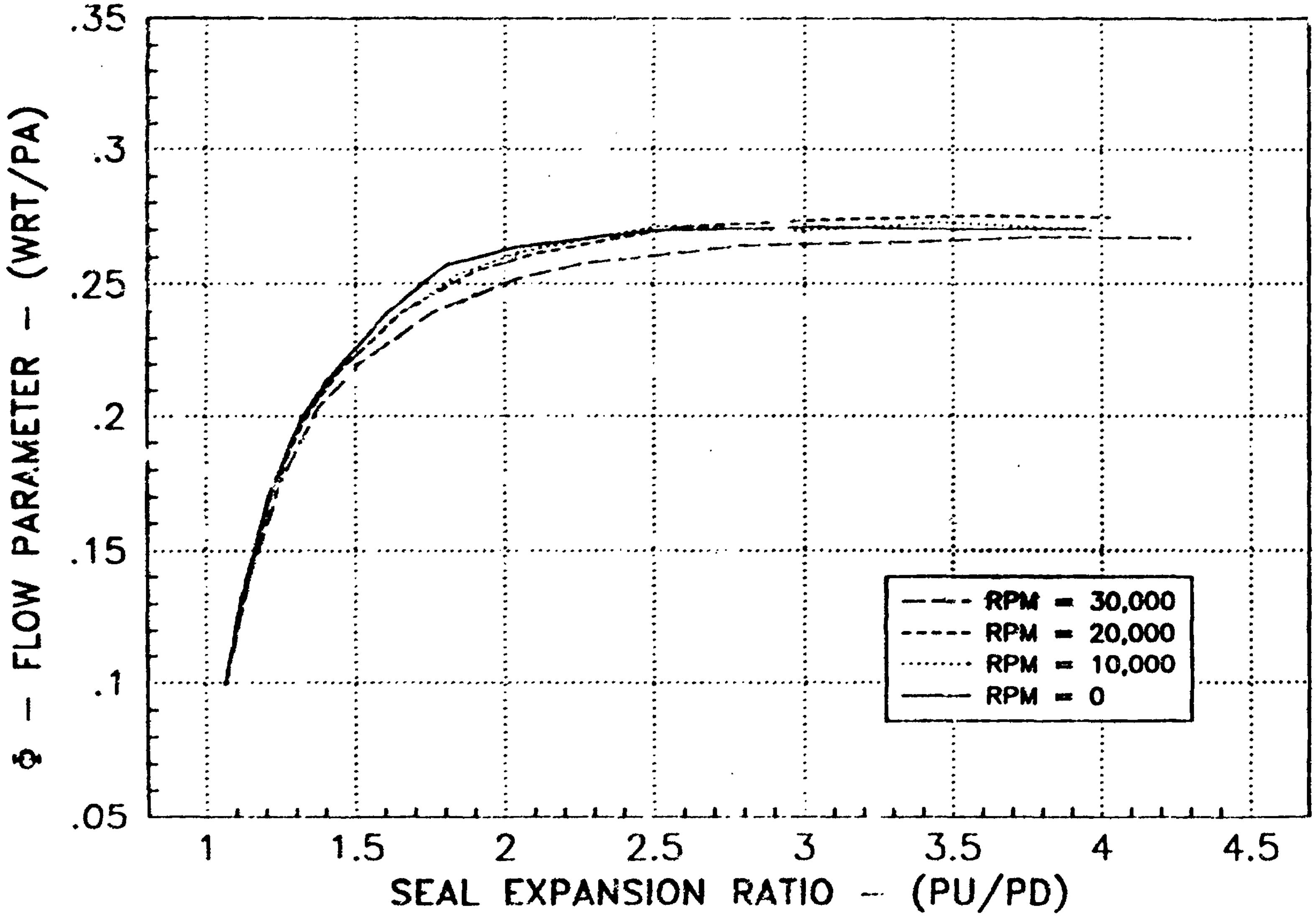


3—D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=70 LAND=0.062" H/C

TEST 17

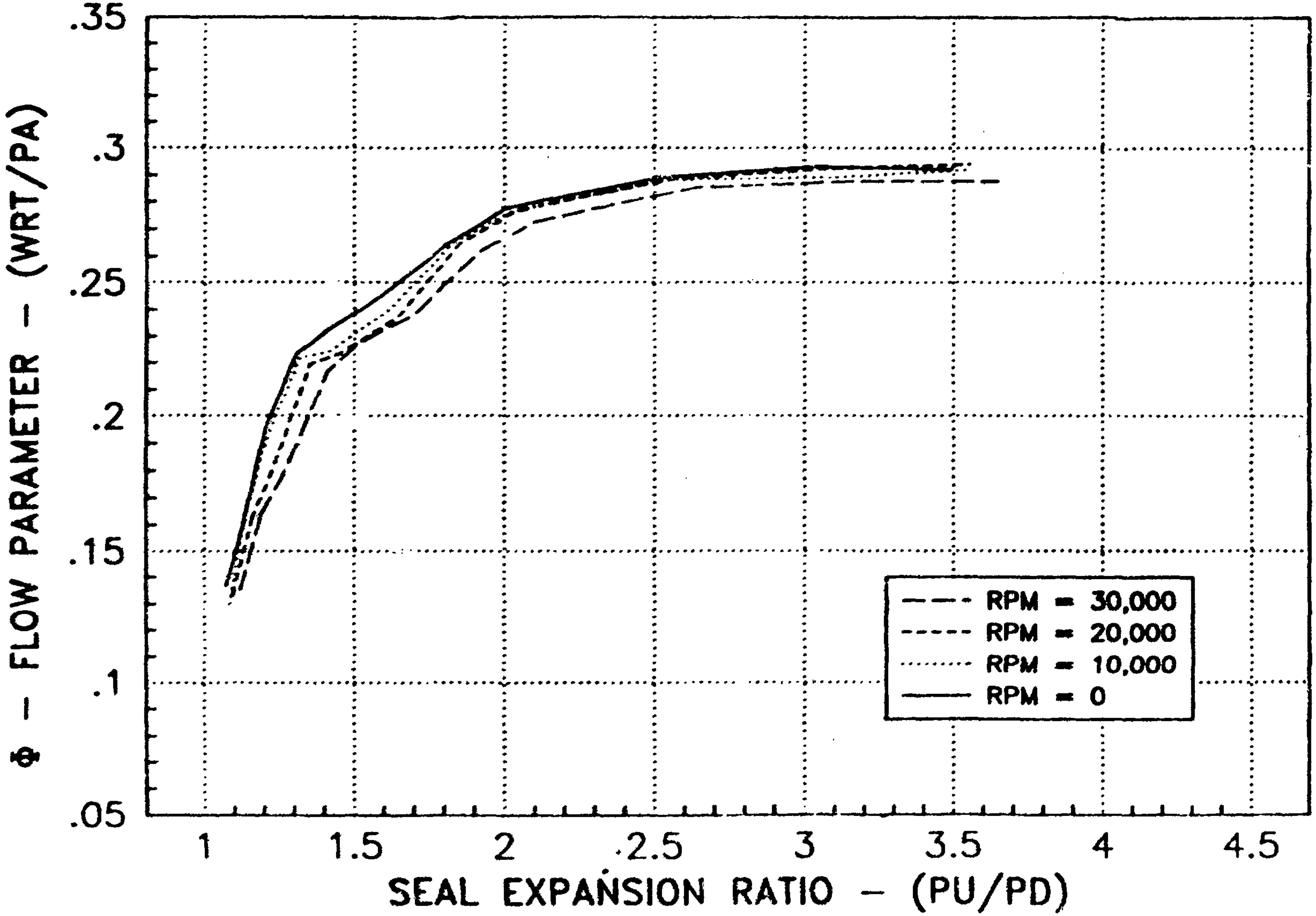


3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010"   KNIFE ANGLE=70   LAND=SOLID SMOOTH
TEST 18



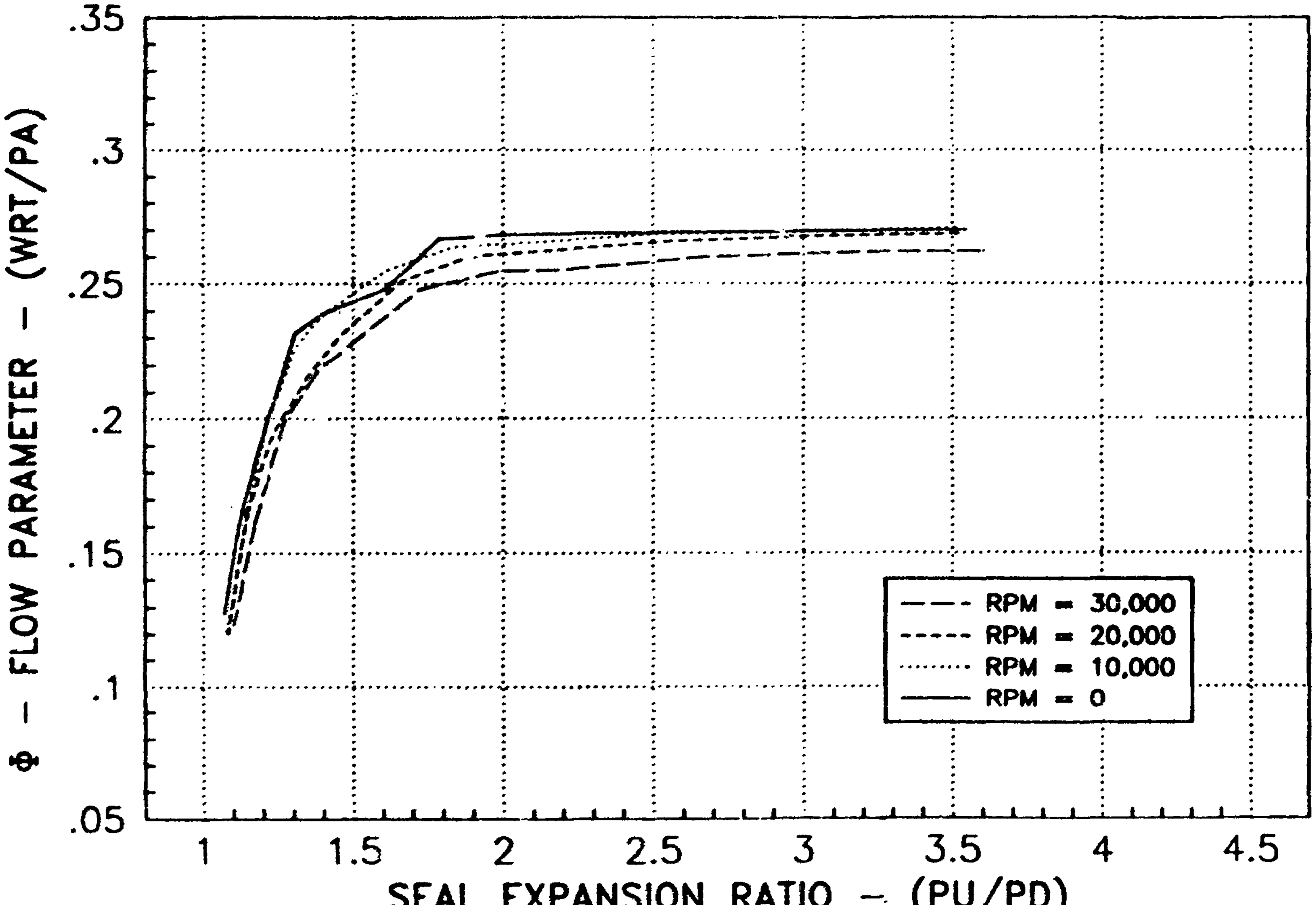
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020" KNIFE ANGLE=70 LAND=0.031" H/C

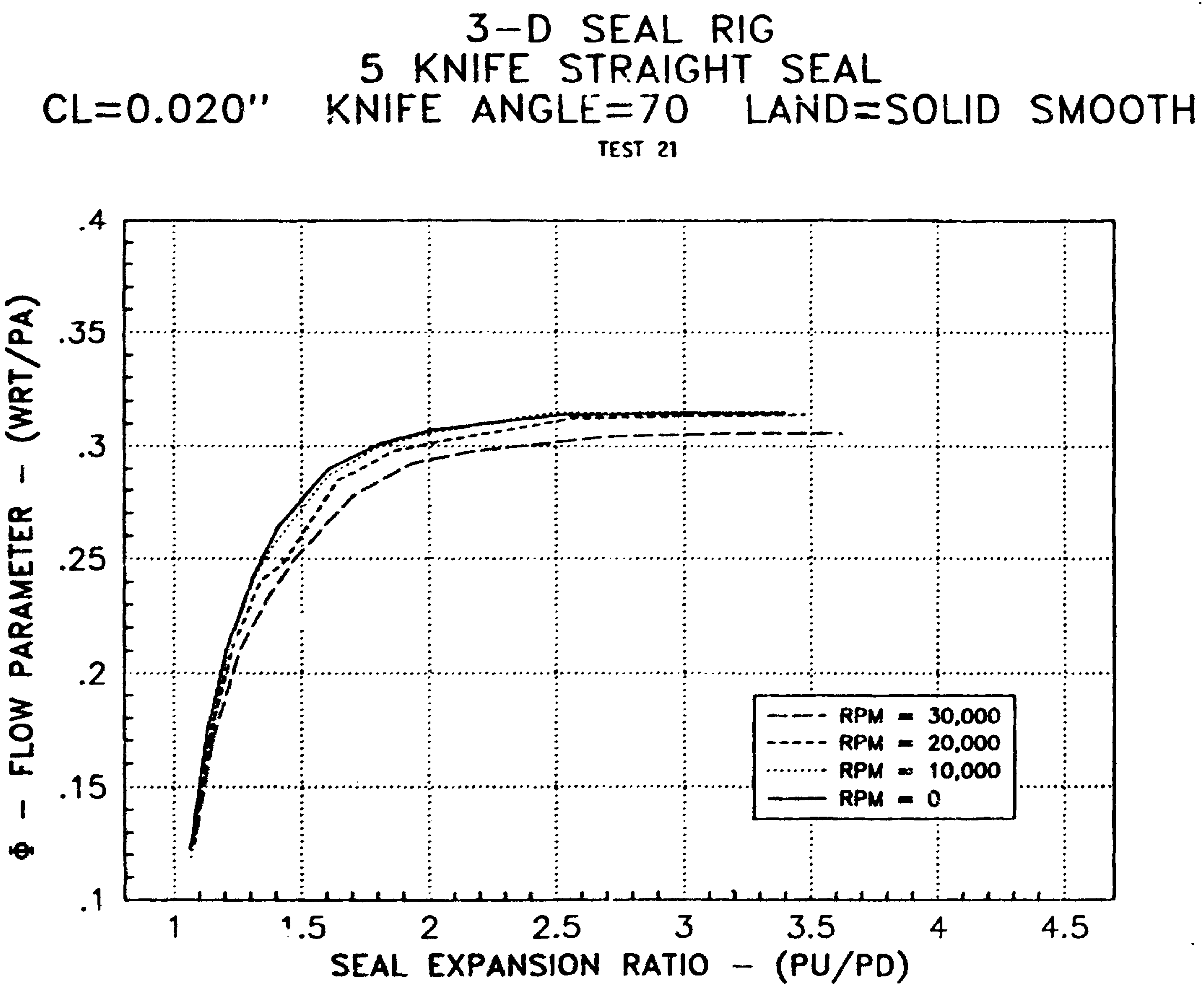
TEST 19



3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020" KNIFE ANGLE=70 LAND=0.062" H/C

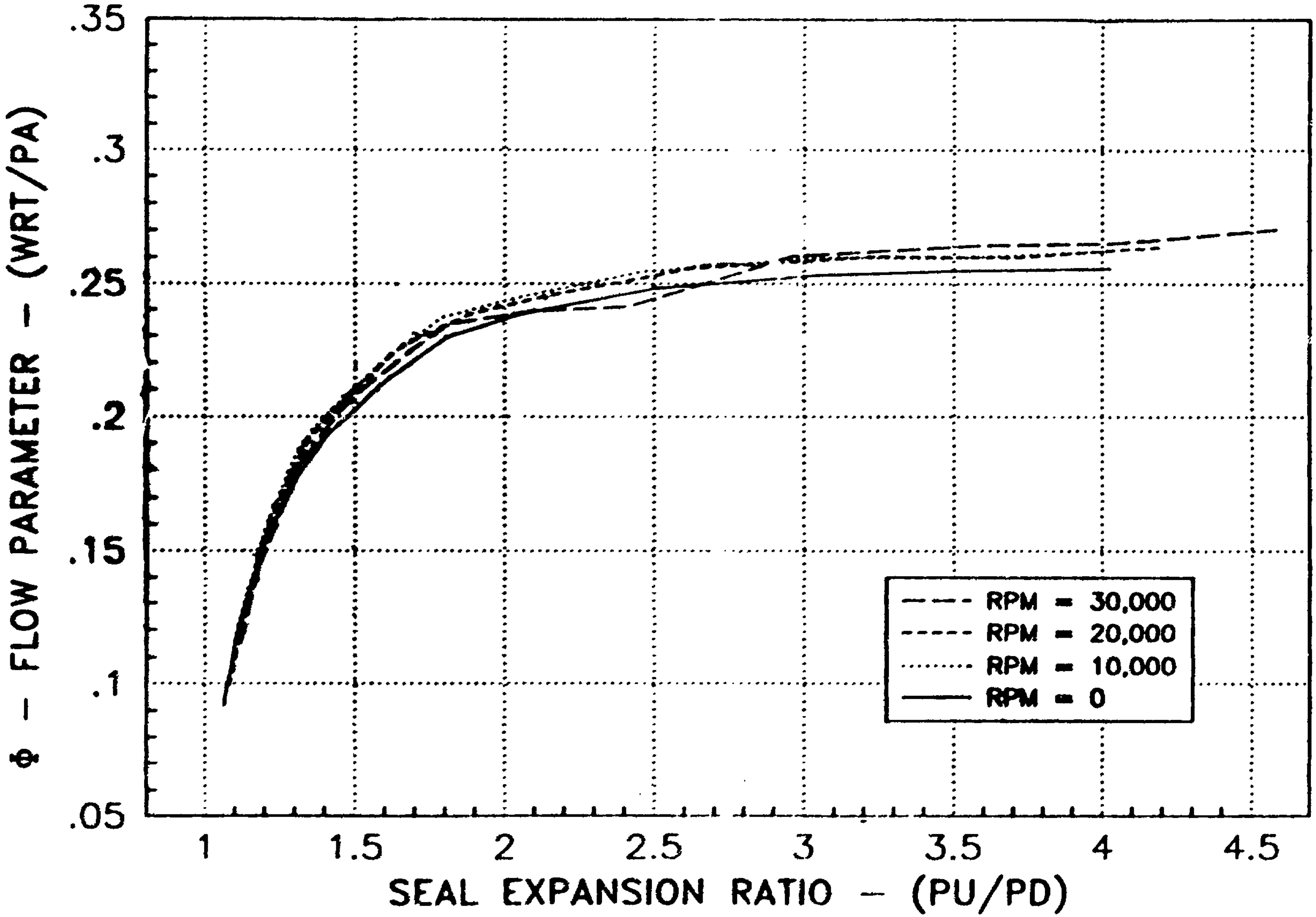
TEST 20

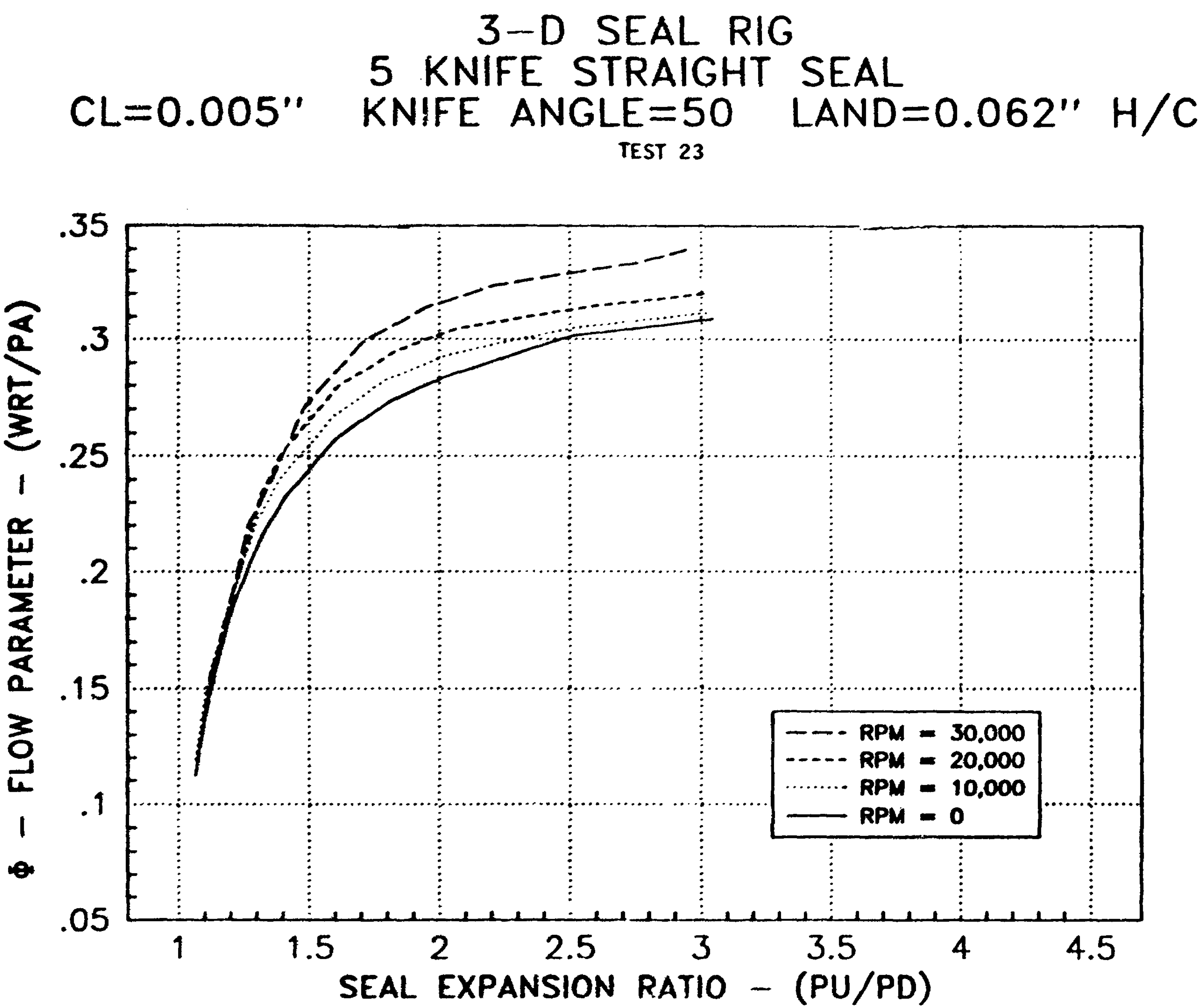



3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020"   KNIFE ANGLE=70   LAND=SOLID SMOOTH
TEST 21
Φ - FLOW PARAMETER - (WRT/PA)
.4
.35
.3
.25
.2
.15
.1
1
1.5
2
2.5
3
3.5
4
4.5
SEAL EXPANSION RATIO - (PU/PD)
RPM = 30,000
RPM = 20,000
RPM = 10,000
RPM = 0

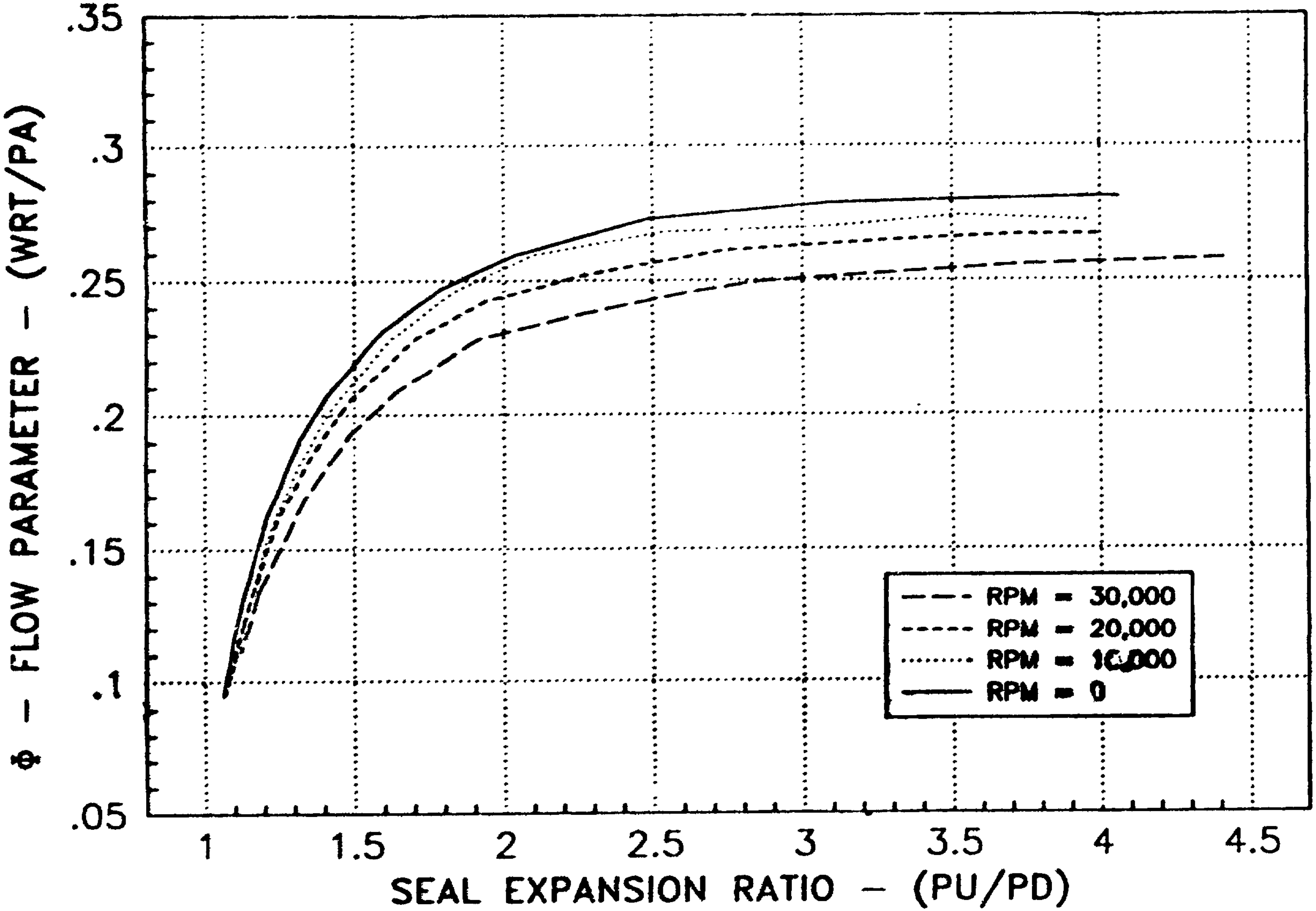
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=50   LAND=0.031" H/C

TEST 22



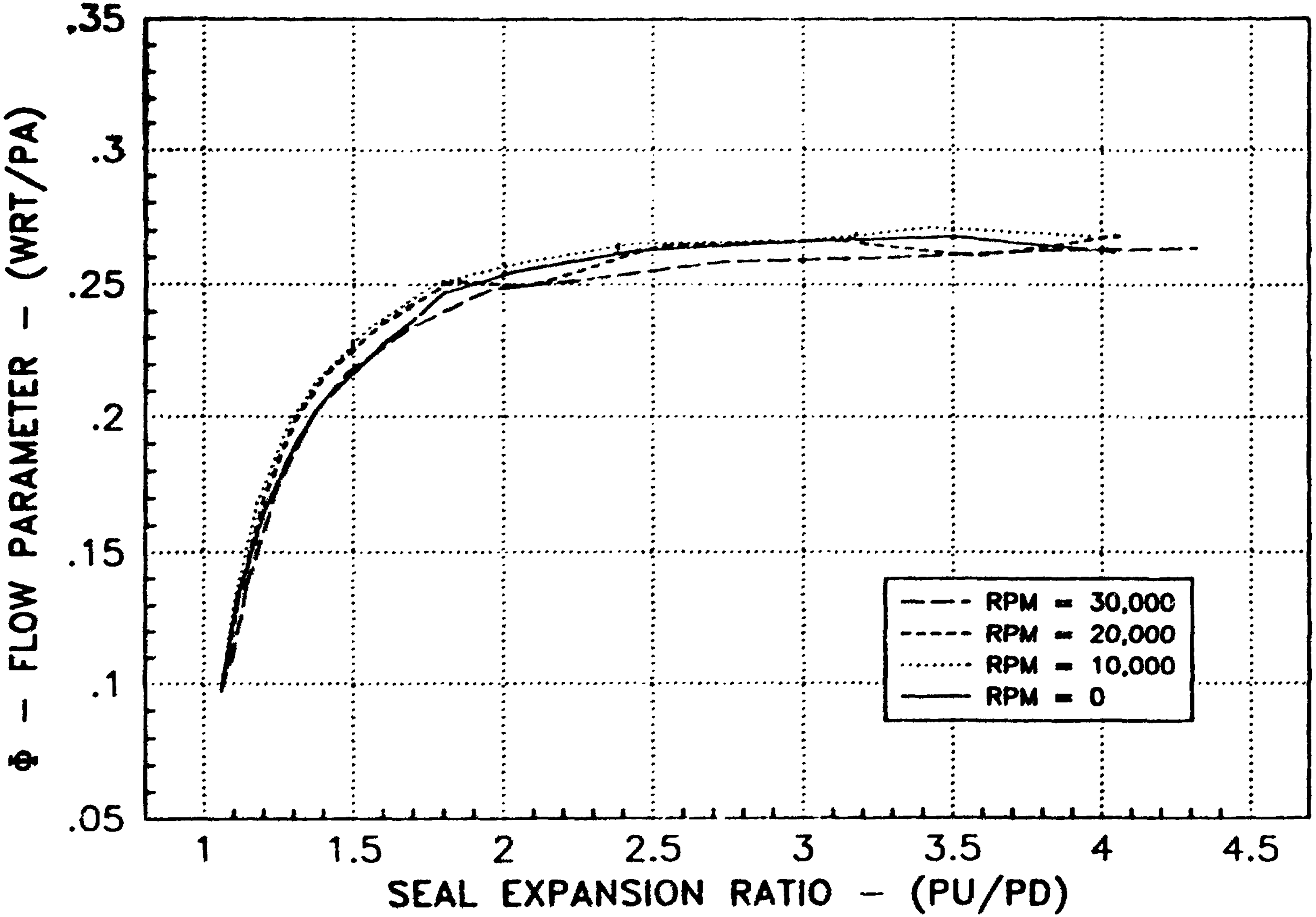

3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005" KNIFE ANGLE=50 LAND=0.062" H/C
TEST 23
Φ - FLOW PARAMETER - (WRT/PA)
.35
.3
.25
.2
.15
.1
.05
1
1.5
2
2.5
3
3.5
4
4.5
SEAL EXPANSION RATIO - (PU/PD)
RPM = 30,000
RPM = 20,000
RPM = 10,000
RPM = 0

3—D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.005"   KNIFE ANGLE=50   LAND=SOLID SMOOTH
TEST 24



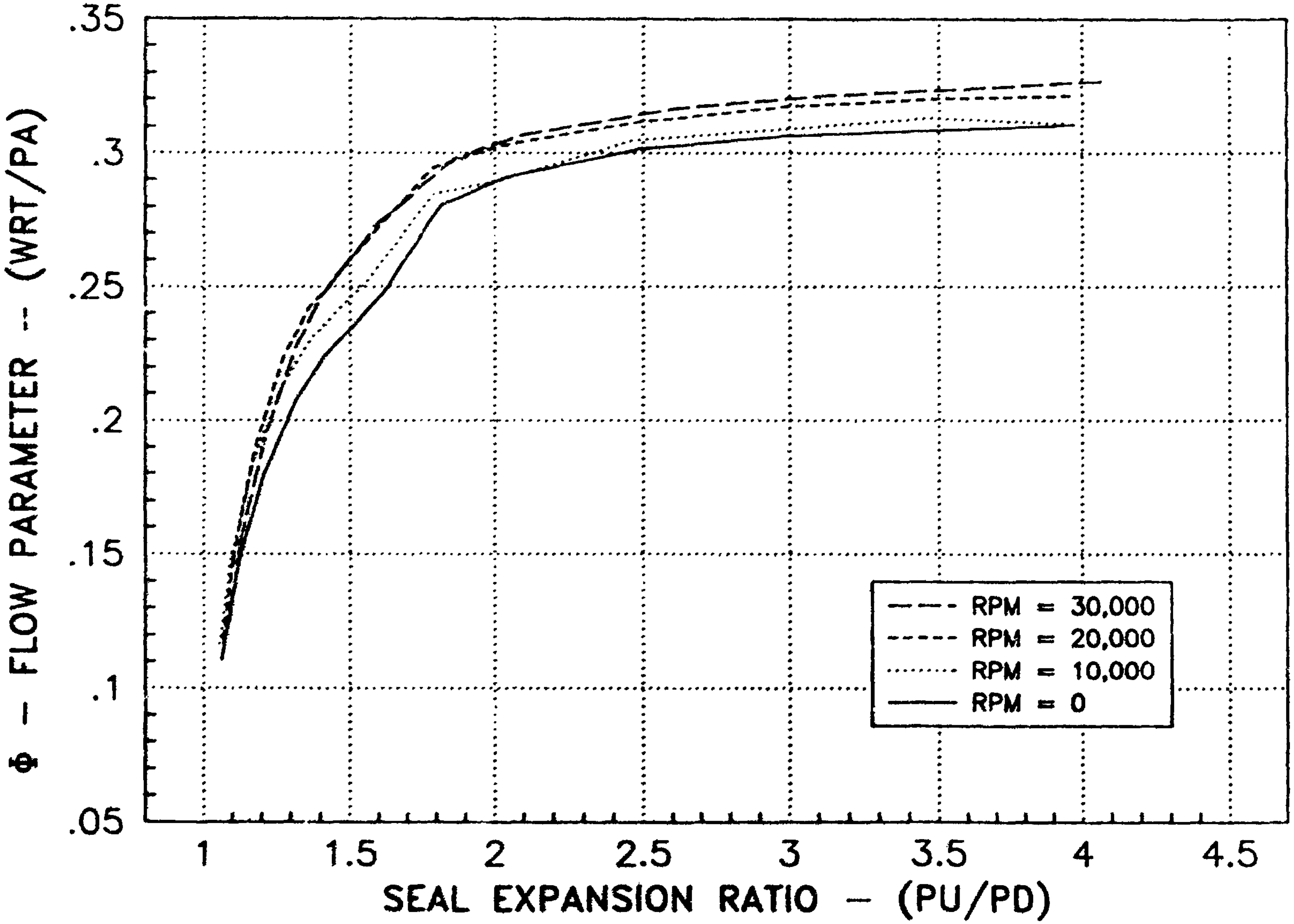
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=50 LAND=0.031" H/C

TEST 25



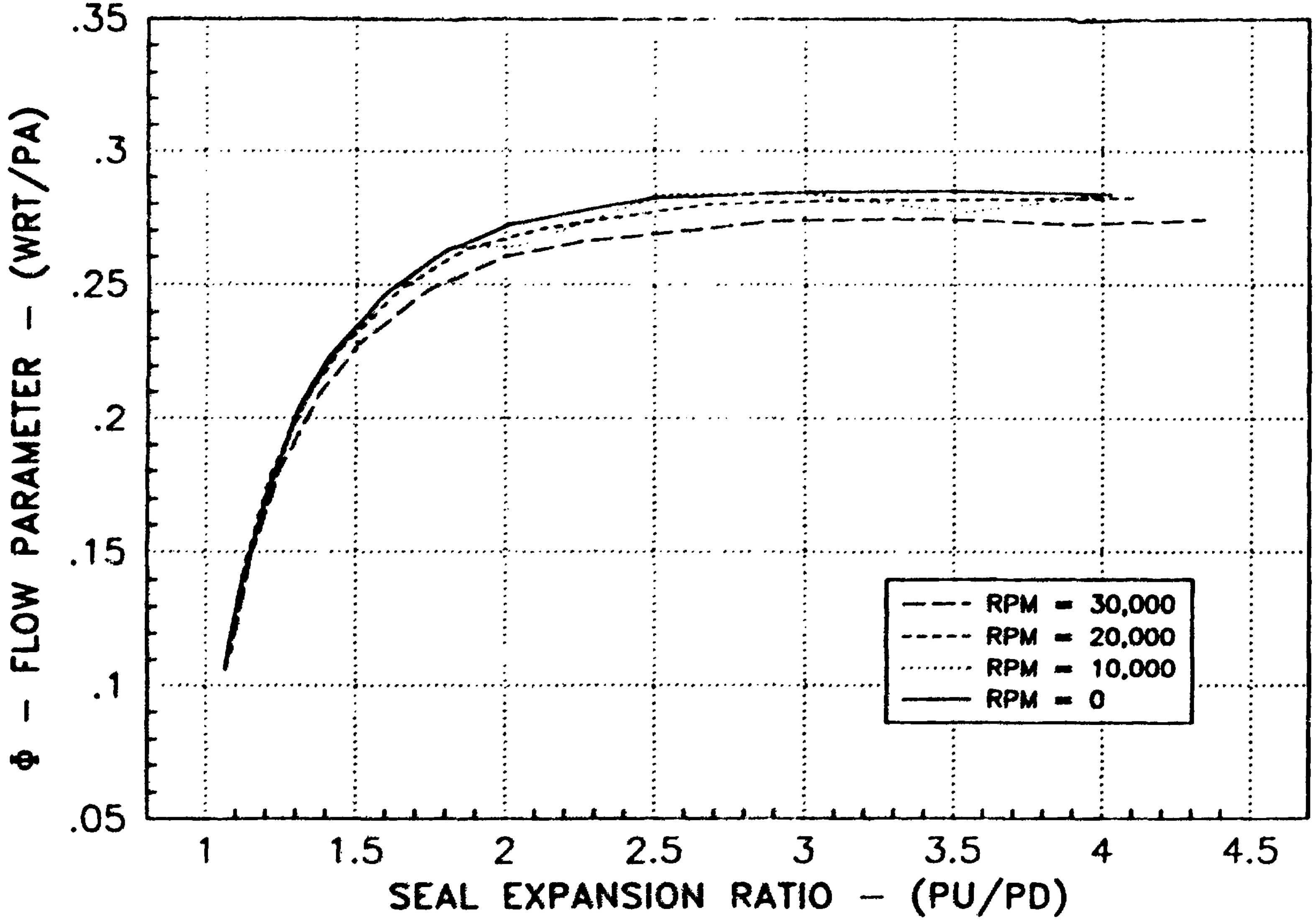
3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010"   KNIFE ANGLE=50   LAND=0.062" H/C

TEST 26



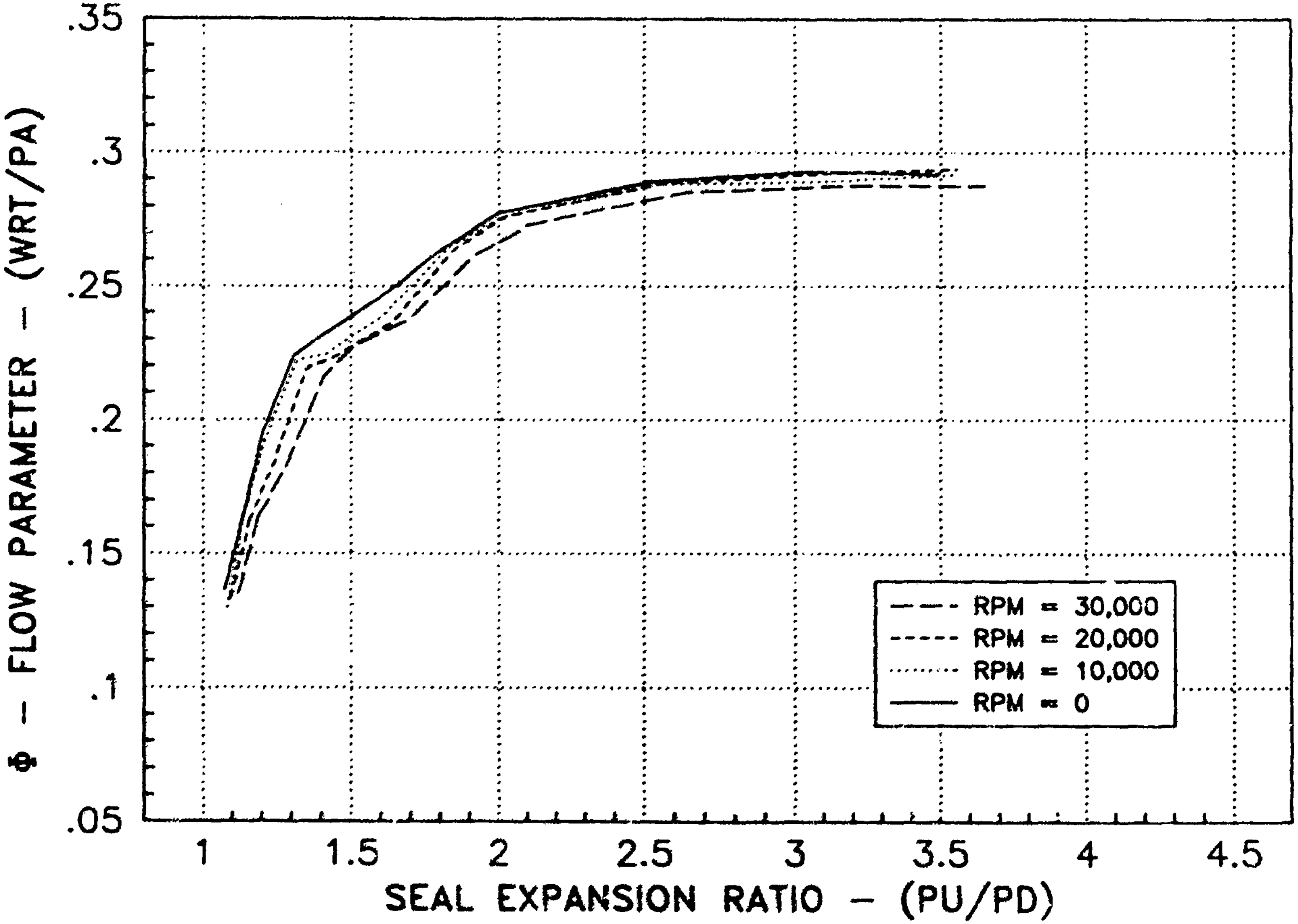
3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.010" KNIFE ANGLE=50 LAND=SOLID SMOOTH

TEST 27

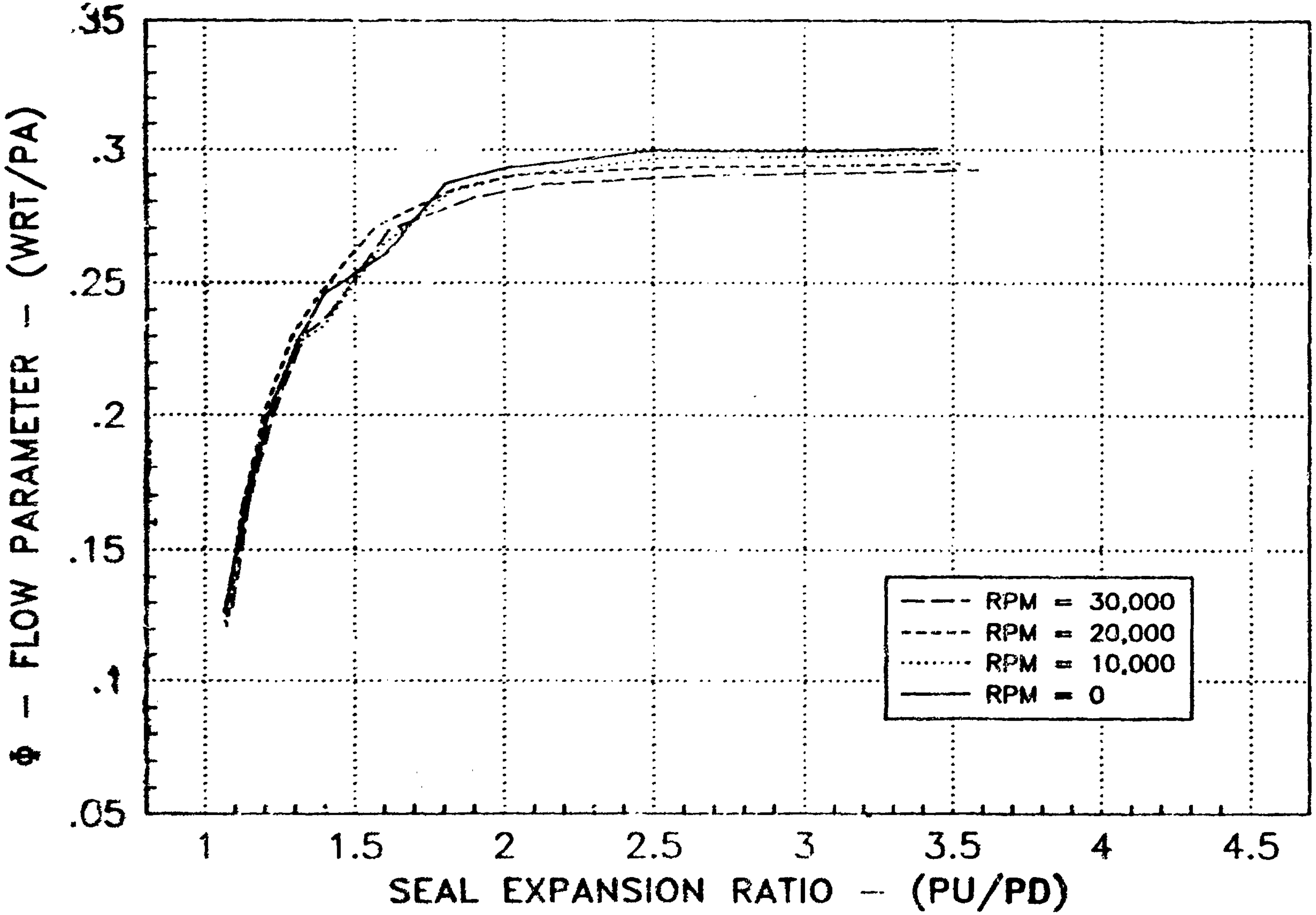


3–D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020" KNIFE ANGLE=70 LAND=0.031" H/C

TEST 28

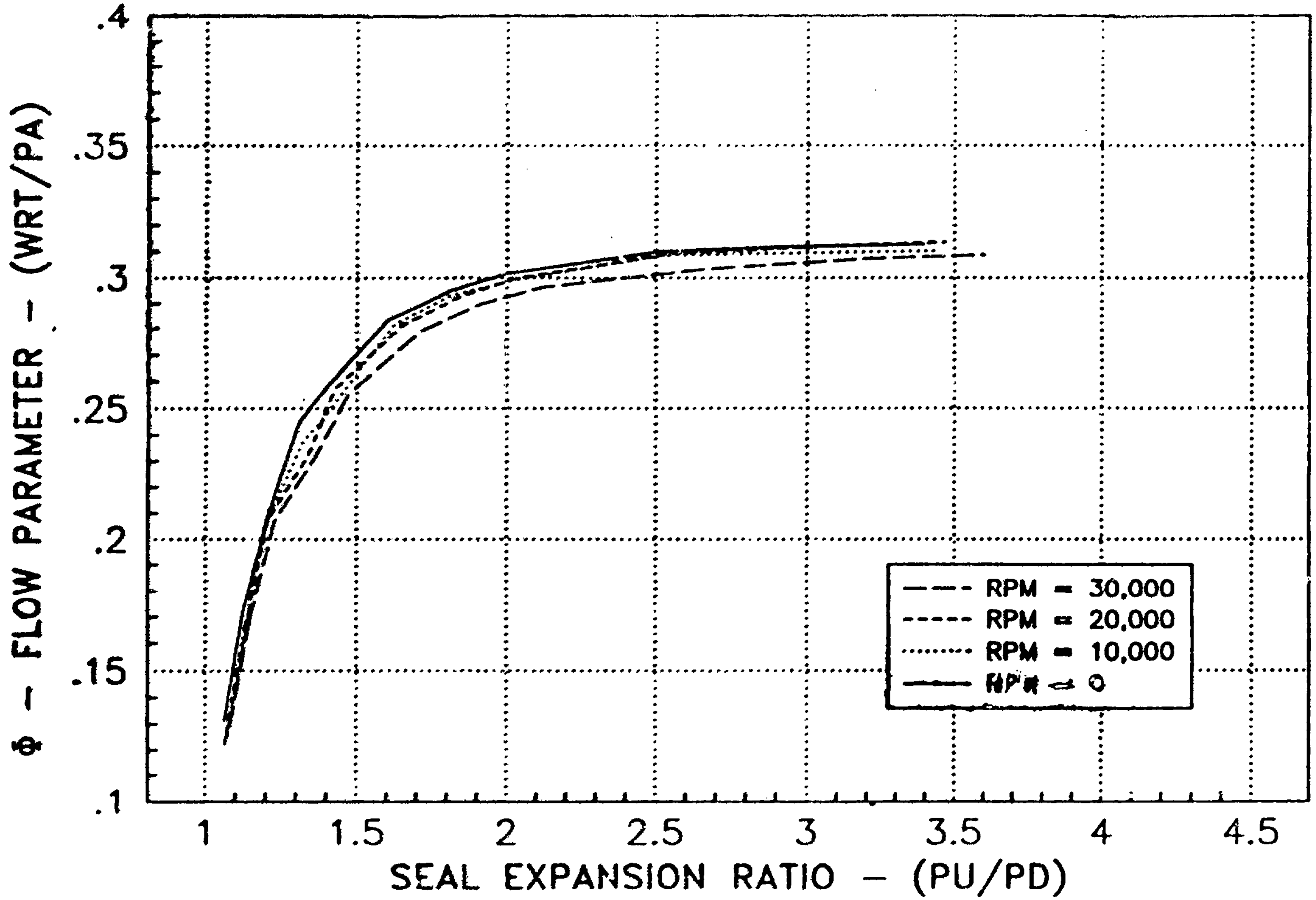


3-D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020"   KNIFE ANGLE=50   LAND=0.062" H/C
TEST 29

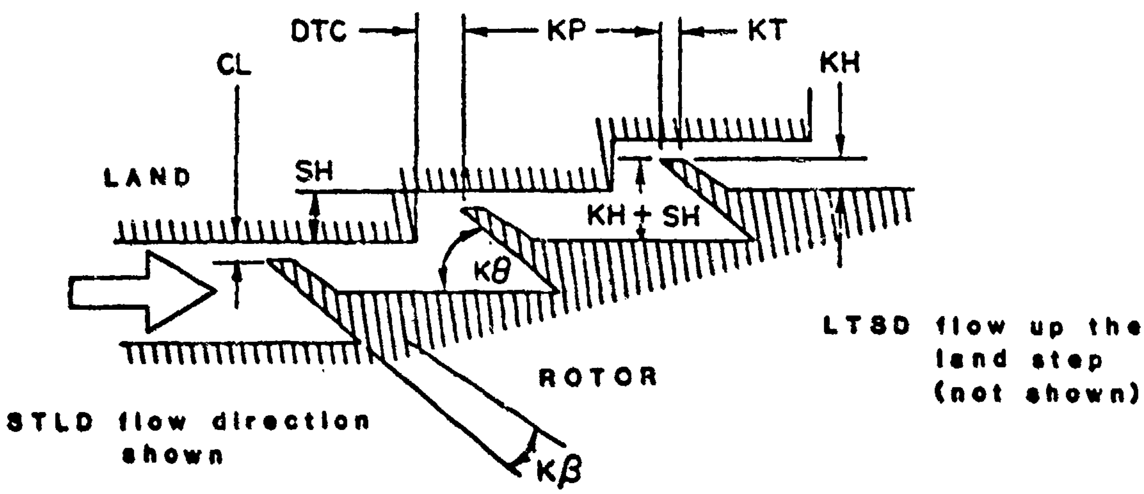


3—D SEAL RIG
5 KNIFE STRAIGHT SEAL
CL=0.020"   KNIFE ANGLE=50   LAND=SOLID SMOOTH

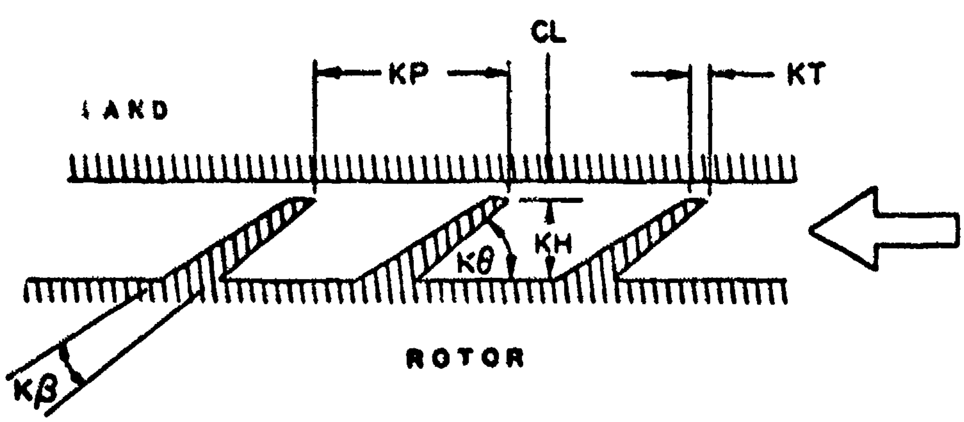
TEST 30



STEPPED SEALS



STRAIGHT SEALS



Labyrinth Seal Nomenclature.

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